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KITE EXPERIMENTS AT THE WEATHER BUREAU.

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By C. F. Marvin, Professor of Meteorology, U. S. Weather Bureau (dated July, 1896).

In November, 1895, the present writer was directed by Prof. Willis L. Moore, the Chief of the Weather Bureau, to consider the subject of devising kites and auxiliary apparatus for the meteorological exploration of the upper air. The definite object was to attain a height of at least 1 mile and, if possible, 10,000 feet or more, and to bring down continuous records of temperature, moisture, pressure, and wind. A considerable acquaintance with the present state of the art of making and flying kites showed that both the form of the body of the kite and the analysis of the action of the forces that affected it demanded fuller consideration than had hitherto been given. In view of the rapidly increasing interest in this subject it seems proper to lay before the cooperating observers of the the Weather Bureau the results that have been attained during the past few months, in order that those interested in the subject may in conducting their own experiments, profit by our experience.

With the advance of the science of meteorology, and especially with the progress in the development of the fundamental laws governing atmospheric phenomena, a growing need arises for accurate knowledge of the conditions of the atmosphere with respect to its motion, temperature, pressure, moisture, etc., not only near the surface of the earth but particularly in the higher strata, where the forces in action have full scope and their effects are unmodified by such disturbing influences as exist near the surface.

Meteorological stations have been maintained on lofty mountain summits, in order to procure the desired information, and many perilous balloon voyages have been made with the express object of making accurate measurements of the atmospheric conditions at all elevations. Some use has been made of captive balloons, and within a few years remarkable results have been obtained in Europe by the use of free balloons of small size equipped with automatic instruments. Having no load of ballast to carry, these balloons when set free shoot upward with great velocity and attain very lofty elevations, whereupon, losing all effective lifting force by reason of the expansion and overflow of gas incident to the great diminution of pressure in the rarified strata of air, the

* Reprinted from the Monthly Weather Review, beginning April, 1896.

partially inflated bag falls to the earth after a comparatively short journey. A notice attached to the balloon gives instructions respecting its disposition, and the finder receives a small reward for its safe return.

It appears, however, that even before balloons were invented, Dr. Alexander Wilson of Glasgow employed tandems of kites "to explore the temperature of the atmosphere in the higher regions." I am indebted to Professor Abbe for the following extract[1] giving an account of Dr. Wilson's experiments, which, owing to their early date and complete and interesting character, deserve special mention:

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Among the more advanced students, who, in the years 1748 and 1749 attended the lectures on Divinity in the University, was Mr. Thomas Melvill, so well known by his mathematical talents, and by those fine specimens of genius which are to be found in his posthumous papers, published in the second volume of the Edinburg Essays, Physical and Literary. With this young person Mr. Wilson then lived in the closest intimacy Of several philosophical schemes which occurred to them in their social hours, Mr. Wilson proposed one, which was to explore the temperature of the atmosphere in the higher regions, by raising a number of paper kites, one above another, upon the same line, with thermometers appended to those that were to be most elevated. Though they expected, in general, that kites thus connected might be raised to an unusual height, still they were somewhat uncertain how far the thing might succeed upon trial. But the thought being quite new to them, and the purpose to be gained of some importance, they began to prepare for the experiment in the spring of 1749.[2]

Mr. Wilson's house at Camlachie was the scene of all the little bustle which now became necessary, and both Mr. Melvill and he, alike dexterous in the use of their hands, found much amusement in going through the preliminary work, till at last they finished half a dozen large paper kites, from 4 to 7 feet in height, upon the strongest, and at the same time upon the slightest construction the materials would admit of. They had also been careful in giving orders early for a very considerable quantity of line, to be spun of such different sizes and strength, as they judged would best answer their purpose; so that one fine day, about the middle of July, when favored by a gentle, steady breeze, they brought out their whole apparatus into an adjoining field, amidst a numerous company, consisting of their friends and others, whom the rumor of this new and ingenious project had drawn from the town.

They began with raising the smallest kite, which being exactly balanced, soon mounted steadily to its utmost limit, carrying up a line, very slender, but of strength sufficient to command it. In the meantime the second kite was made ready. Two assistants supported it between them in a sloping direction with its breast to the wind and with its tail laid out evenly upon the ground behind, whilst a third

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[1] Extract from Biographical account of Alexander Wilson, M. D., late Professor of Practical Astronomy in Glasgow, by the late Patrick Wilson, A. M., Professor of Practical Astronomy in the University of Glasgow. Transactions of the Royal Society of Edinburgh, Vol. X, Part II, pp. 279–297. 1825.

This memoir of Dr. Wilson, after being read at the Royal Society, February 2, 1789, was withdrawn by its author for the purpose of making some alterations upon it, and was never returned for publication. It was found, however, among the papers of Mr. Patrick Wilson, and is now printed with the consent of his family.

[2] As no public notice has hitherto been taken of this matter, though Mr. Wilson had always some thoughts of doing so, it is hoped that the following detail will not prove unacceptable or tedious to the reader.

person, holding part of its line tight in his hand, stood at a good distance directly in front. Things being so ordered, the extremity of the line belonging to the kite already in the air was hooked to a loop at the back of the second, which being now let go, mounted very superbly, and in a little time also took up as much line as could be supported with advantage, thereby allowing its companion to soar to an elevation proportionally higher.

Upon launching these kites according to the method which had been projected, and affording them abundance of proper line, the uppermost one ascended to an amazing height, disappearing at times among the white summer clouds, whilst all the rest, in a series, formed with it in the air below such a lofty scale, and that, too, affected by such regular and conspiring motions as at once changed a boyish pastime into a spectacle which greatly interested every beholder. The pressure of the breeze upon so many surfaces communicating with one another was found too powerful for a single person to withstand when contending with the undermost strong line, and it became, therefore, necessary to keep the mastery over the kites by other means.

This species of ærial machinery answering so well, Mr. Wilson and Mr. Melvill employed it several times during that and the following summer in pursuing those atmospherical experiments for which the kites had been originally intended. To obtain the information they wanted, they contrived that thermometers, properly secured, and having bushy tassels of paper tied to them, should be let fall at stated periods from some of the higher kites, which was accomplished by the gradual singeing of a match-line.

When engaged in these experiments, though now and then they communicated immediately with the clouds, yet, as this happened always in fine weather, no symptoms whatever of an electrical nature came under their observation. The sublime analysis of the thunderbolt, and of the electricity of the atmosphere, lay yet entirely undiscovered, and was reserved two years longer for the sagacity of the celebrated Dr. Franklin. In a letter from Mr. Melvill to Mr. Wilson, dated at Geneva, 21st of April, 1753, we find, among other particulars, his curiosity highly excited by the fame of the Philadelphian experiment, and a great ardour expressed for prosecuting such researches by the advantage of their combined kites. But, in the December following, this beloved companion of Mr. Wilson was removed by death, to the vast loss of science, and to the unspeakable regret of all who knew him.

The limits of the present article preclude giving anything like a full historical notice of the use of kites for scientific purposes or for securing observations of the meteorological conditions of the upper air. A few references only will be given if with no other object than simply to show that the application of kites to practical, useful purposes is by no means a novel idea of the last few years, as some appear to think. Mr. W. R. Birt[1] on the 14th of September, 1847, flew a specially constructed kite at the Kew Observatory, in order to test and demonstrate its usefulness in obtaining measures of temperature, humidity, wind velocity, etc. The kite was caused to assume a more fixed position in the air by restraining it by means of three strings secured to the ground at the three corners of a comparatively large equilateral triangle.

Admiral Bach,[2] when in command of the *Terror*, used a kite to obtain the temperature of the upper air in Hudson Strait.

Espy, in his Philosophy of Storms, p. 167, states that "The Franklin Kite Club, at Philadelphia, have lately dis-

[1] Phil. Mag., Vol. XXXI, 1847, p. 191.

[2] Quart. Journal, Met'l Soc., Vol. IX, 1883, p. 63.

covered[1] that in those days, when columnar clouds form rapidly and numerously, their kite was frequently carried upward nearly perpendicularly by columns of ascending air." The existence, for brief periods, of strongly ascending currents of air has also been repeatedly noticed in the Weather Bureau experiments.

E. Douglas Archibald[2] in England advocated the use of "A kite, or a series of kites flown tandem, that is, one above the other" for showing the direction of air currents, and for attaching thermometers, anemometers, etc., so that the condition of the air in the upper currents could be determined.

Experiments of this character were first regularly begun by Archibald[3] in November, 1883; the particular object in view being to ascertain the increase of wind velocity with elevation, Biram's anemometers being attached to the kite string for this purpose. The kites were diamond shape, with tails, and were flown tandem. Flax string was first employed, but acting upon the suggestion of Sir William Thomson, steel pianoforte wire was substituted, on which Archibald remarks:

> This I have found a great improvement on the string. It is double the strength, one-fourth the weight, one-tenth the section, and one-half the cost.

A summary of the results obtained by Archibald will be found in Nature, Vol. XXXIII, 1885–86, p. 593.

Archibald also devised and made some use of a captive kite balloon which he described in Nature, Vol XXXVI, 1887, p. 278. This combination was designed to obviate the detrimental action of the wind on the balloon surfaces. As the balloon kite has often been proposed as of great utility it will be worth while to notice the results of Archibald's tests. The balloon had a capacity of 113 cubic feet; the octagonal kite measured 7 by 9 feet. Twelve hundred feet of steel pianoforte wire was paid out. Wind at Greenwich 12 miles per hour. The angles of elevation were as follows: Balloon alone, 38°; wire near ground, 18°. Balloon with kite, 41.5°; wire near ground, 35°.

It is observed the effect of the kite was to increase the angular elevation of the balloon 3.5°, but the angle itself was only 41.5°. Now, any good kite is easily capable of sustaining 1,200 feet of steel wire so that both the kite and the wire will have an angular elevation of at least 60° and 58°, respectively. It appears, therefore, that under favorable conditions the kite is able to help the balloon, but the balloon, on account of the large surface exposed to the wind, will only serve to drag down the kite to a much lower position than it would attain alone. If little or no wind blows the balloon alone is sufficient, and is only trammelled by the presence of a kite.

In 1890 William A. Eddy, of Bayonne, N. J., "began experi-

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[1] Probably about 1837.
[2] Quart. Journal, Met'l Soc., Vol. IX, 1883, p. 63.
[3] Nature, Vol. XXXI, 1884–1885, p. 66.

ments to determine the relations between the width and length of the ordinary kite." The object in view was "to evolve the best form of kite to be used in raising self-recording meteorological instruments to a great height, because many important problems in meteorology would be affected by investigations of the upper air currents." Beginning with star and hexagon kites with tails, Mr. Eddy was led to the re-invention of the so-called Malay tailless kite, a form which within recent years has, perhaps, been more extensively used for scientific purpose than any other.

The kite experiments made at Blue Hill under the direction of Mr. A. Lawrence Rotch, have aimed particularly to secure observations of the atmospheric conditions at as high elevations as possible. The work appears to have begun in the fall of 1894. Kites of the Malay or Eddy type were used at first and other forms later. A number of actual records of the temperature, pressure, and moisture contents of the air, also of wind velocity, have been obtained at various elevations up to something less than 4,000 feet, and the work reflects much credit opon the proprietor of the observatory and his assistants.

Probably the most remarkable modern inventor of kites is Mr. Lawrence Hargrave, of Sydney, N. S. W., Australia. Mr. Hargrave contributed an important paper to the meeting of the Aeronautical Congress, held in Chicago at the time of the World's Fair, 1893. In this paper were described models of flying machines and of the peculiar cellular kites which were afterwards greatly developed by the inventor and have since become widely known among kite experts. The description of the Hargrave cellular kites, which appeared in the American Engineer for April, 1895, p. 193, has brought these kites to the attention of some of the experimenters in the United States. In an article entitled "A Weather Bureau Kite," in the WEATHER REVIEW, for November, 1895, the writer credited Mr. S. A. Potter with being "the first in the United States to successfully construct and fly kites of this kind." The Aeronautical Annual for 1896, which did not reach the hands of the writer until after the article referred to had been written, contained accounts of successful experiments with the cellular kites by both Charles H. Lamson and J. B. Millet. The date of Mr. Lamson's experiments is not given. The work of Mr. Millet was done during August and September, 1895. Experiments were also made at Blue Hill with cellular kites in August, 1895, which were described in the Boston Herald, August 19, 1895, and Springfield Republican, August 21, 1895. It does not seem that this type of kite was then regarded with much favor or that further experiments with this form were actively pushed. Mr. Eddy also tried the cellular kites, at first on September 1, 1893, and again in December, 1895, but with unsuccessful results. He was finally successful in flying the kite independently for the first time on December 9, 1895. Mr. Potter's work can therefore scarcely

claim to be first in mere point of time, the results, however, were highly successful and promising and this type of kite at once superceded all other forms in the Weather Bureau work.

The kite experiments at the Weather Bureau were first taken up by Mr. Alexander McAdie and Mr. S. A. Potter, only semiofficially, however. The work began early in November, 1894, and was carried on wholly outside of office hours and in addition to other regular duties. Nevertheless, owing to the industry and skill of Mr. Potter a large number of kites, mostly of the Malay type, were flown successfully from time to time at Mr. Potter's country residence. No methodical record of the progress of the work appears to have been kept, nor were instrumental or other accurate observations made of the results attained. A small thermograph, constructed mostly of aluminum, was purchased during the following spring from Richard Bros., and records of air temperatures at elevations of a few hundred feet were obtained on several occasions during the ensuing summer. The thermograph proved to be imperfect and ill adapted to the work. On one occasion a tandem of eleven Malay kites was successfully flown. A suitable reel for controlling the string with which the kites were flown was found indispensable, and a very convenient and efficient affair was devised by Mr. Potter.

The work finally assumed the character of an official investigation only in the fall of 1895. Prof. Willis L. Moore, as the new Chief of the Weather Bureau, at once recognized the great importance of extending the observations of the Weather Bureau into the upper atmosphere in order to advance the knowledge of storm generation and improve the daily forecasts. Mr. McAdie being detailed for duty at the office in San Francisco, Prof. H. A. Hazen, with Mr. Potter's assistance, was directed, on October 14th, 1895, to make experiments for the purpose of devising and perfecting an appliance that might be used in observing the meteorological conditions of the upper air. Subsequently, namely, November 18, 1895, the writer was also directed by Professor Moore, in addition to his other duties, to investigate the problem of constructing appliances for carrying meteorological instruments into the upper air. Professor Moore has himself proposed two different devices as being possibly of use in the solution of the problem in hand; namely, the combination of a kite and balloon, by which the desired observations can be obtained not only when the wind blows, but during calms or when the wind is too light to make the flying of kites alone successful, and a device constructed on the general plan of what we may call a soaring top. In fact, a toy of this character appears to have first suggested the idea to Professor Moore. The toy consists of a thin metal or card-board disk, cut up into a number of equally distributed radial gashes extending nearly to the center. The surfaces are then twisted or bent so as to take an oblique position, screw propeller fashion, in reference

to the general plane of the disk. In fact, the disk resembles very much a small fan wheel, such as is commonly seen on electric fans. At the center the disk is fitted with a small axle at right angles. A suitable holder is provided, and when the disk is given a high speed of rotation by the unwinding of a string from the axle, as in spinning a top, the disk lifts out of the holder and soars to a considerable height in the air. Such a device, on the proper scale, either started at high velocity from the earth, or carrying its motor with it, may possibly be made to accomplish the desired results.

Professor Moore's aim has been to reach higher altitudes than those which have been heretofore attained by ordinary kites. Special funds were not available for costly experiments with balloons or combination affairs; moreover, kites themselves not only on account of their slight cost but also because of their general effectiveness, seemed the most promising subject for the first investigations. The effort has been therefore to develop the kite to the highest point of efficiency and ascertain to what extent it can be utilized in reaching elevations of from 1 to 2 miles or more.

The work at the present time is still in an experimental stage as it were, but it is believed enough has been accomplished to justify publishing preliminary results in the hope that the progress already made in the Weather Bureau investigations will stimulate to new efforts, and be helpful to the several private experimenters independently at work on the same problem, and if possible, therefore, hasten complete success.

On scientific methods in kite investigations.—While the literature on kites describes an almost endless variety of forms and shows some to have been employed in useful ways, that is, for drawing wagons, sleds in the Arctic regions, boats, etc., or for other purposes and for securing meteorological observations, of which latter use we have mentioned above a few cases only, yet no writer seems to have fully discussed the action of the kite from a scientific standpoint, or analyzed and explained the physical and mechanical principles involved therein. Sir Isaac Newton is said to have taught the boys how to fly their kites, but if one desires to learn much about the mechanics of a kite in action, a search in kite and aeronautical literature will prove fruitless, or nearly so; at least such has been the experience of the writer in the partial search that he has thus far been able to make. Some investigators in recent times, while spending years of work with the avowed purpose of developing the kite for useful purposes, have either assumed the deplorable attitude of discrediting the value of technical or so-called theoretical considerations as applied to kites, or have struggled on by cut-and-try processes in blissful ignorance of the real character of those laws of nature whose operation they seek to control.

It is unfortunate, to say the least, that any investigator of kites of the present day, having the benefits of modern ad-

vanced education, should entertain the scornful regard that seems to be current with some for the "theory" of kite flying, especially when the history of applied science affords such remarkable illustrations of the immense debt *practice* owes to *science*. There could be no greater mistake than to contemptuously confound science with theory. No more striking instance of the efficacy of scientific methods can be cited than to outline and contrast the growth of the steam engine and electric generators, motors, etc. Although Hero, 120 years B. C., described crude forms of heat engines, steam engines did not begin to be really useful until about the middle of the 17th century. For nearly 200 years thereafter the steam engine underwent a slow and tedious evolution, improving but little in the hands of men ignorant of the laws of thermodynamics. In fact, those laws were quite unknown. Towards the close of this period such men as Carnot, Joule, Clausius, Thomson, and others began to develop the principles of thermodynamics, and Rankine, less than forty years ago, with a master's hand, applied these principles to the practical problems in steam engineering. From this point on the development was very rapid. What 200 years, yes, 2,000 years, counting from Hero, failed to make of the steam engine was effected in a score of years when science pointed the way. The steam engine came into existence and underwent its slow and tedious development by blind experimentation before the rationale of its action was known or understood. The reverse is the case with electric generators, motors, etc. All the principal elements of their theory had been fully developed before the devices were invented. The result is that almost the highest possible state of perfection of these inventions was attained in a few years. Not only was the theory already available but it was developed and applied at every point in the construction and operation of these wonderful machines. The world now stands amazed at the marvelous rapidity of this growth. In the face of such facts as these, can anyone fail to perceive the importance and advantage of formulating the physical laws involved in the operation of any of nature's forces? Let us hope, therefore, that those who seek to develop and perfect the kite in order to apply it to useful purposes will help first to formulate the laws of all the actions involved.

The construction and flying of kites on a large scale is purely and only an engineering problem. It is simply a question of stresses and strains, a question of the strength and resistance of materials, of the operation and equilibrium of certain well-defined forces. In fact, every element of the problem comes within the domain of ordinary mechanics and physics. Kites are amenable to development by the same engineering methods as those that have produced such wonderful results as the Forth Bridge, the Brooklyn Bridge, the Eiffel Tower, the Ferris Wheel, swift ocean steamers, those famous yachts Mayflower, Vigilant, Puritan, Defender, and others. Now that it

is desired to put kites to certain useful applications, it is urged upon those who seek to effect this development that they discard the primitive cut-and-try method and adopt modern engineering methods. The cut-and-try method is good in a certain sense; it is like nature's method of "natural selection," but its operation is exceedingly slow. If time enough is expended in constructing and testing all conceivable kinds of kites, selecting the best, rejecting the inferior, it is possible that a kite may be evolved approaching the maximum possible efficiency, but the engineer has a short cut to this result. He analyzes the action of the kite in every detail; the efficiency of every element is studied separately. By these methods he is soon able to discover and lop off this or that useless member, to increase the efficiency of others and to introduce new members of peculiar and useful function.

When kites are used for carrying strings or ropes to inaccessible distant points, as from a stranded ship to the lee shore, or when used for transportation, as in pulling wagons, or towing boats, it is the object of the constructor to obtain the greatest possible tension or pull on the string, as held by the manipulator at the lowest end near the ground. But for meteorological use we need to have the greatest possible lifting power at the kite end. We must, therefore, develop the vertical and diminish the horizontal component of the pull on the string.

To be more specific, the kind of information needed, for example, is: (1) What is the relative lifting power in a given wind, square foot for square foot, of the single-plane kites, as compared with the cellular kites? (2) In cellular kites, (*a*), how near can the lifting surfaces be to each other without detrimental interference? (*b*) How short a distance may exist between the forward and after cell without the one impairing the effectiveness of the other? (*c*) What length, fore and aft, is the most effectual for the sustaining surfaces? (*d*) What is the most appropriate form and arrangement of the bridle, not only to secure the most satisfactory action of the kite under winds of variable force, but to likewise distribute the strain upon the framework so that lightness, but yet not corresponding weakness of construction, may obtain? (3) In general, for any kite, what is the best angle of incidence? (4) What is the loss due to the pervious structure of the cloth, as compared with paper or balloon fabric, etc.? These are but a few of the elements of the kite problem that need to be separately studied and in respect to which the maximum possible useful effects need to be developed and rendered available to the kite builder.

The writer has been led to make these remarks because so little or none of this kind of work appears to be contemplated by the several experimenters now independently at work trying to render the kite useful for meteorological and other purposes. Moreover, the above considerations should convince one that a line of analysis seeking to develop all the elements

of kite behavior and formulate their relations is the shortest path to the complete solution of the problem.

THE WEATHER BUREAU WORK.

A few remarks describing the management of kites will enable the reader, unfamiliar with what we may call modern scientific kite flying, to form an idea of how the work is carried on. Details of the forms and construction of the kites will be given later. The kites range in size from 6 to 10 feet high, and are, therefore, easily carried about by one person.

The act of starting off or flying any of the larger kites is a very simple matter, especially when the wind is favorable and the kite a good flyer. With steady winds of about 15 miles per hour, the kite when faced to the wind will generally fly right up from the hand, sailing away and upward at an angle of from 30° to 50°. It is necessary only to keep the string under some tension as it is paid out. When the wind is rather feeble, especially if very light at the surface, it will generally be necessary for an assistant to carry the kite off some distance to leeward; seven or eight hundred feet is often not too far. When a favorable puff of wind is felt the assistant tosses the kite upward into the air. At the same moment the string, if managed by a reel, is wound in with sufficient rapidity to cause the kite to fly until fully sustained by the wind. A reel for managing the string is quite indispensable for extensive experiments, but in its absence it may be necessary in starting the kite in light winds to walk briskly to windward. It is almost impossible to describe the means and artifices employed by the skillful operator in managing kites that fly badly, or in working a kite up through strata that have feeble, fitful motion into stronger, steadier currents. Skill of this sort can be acquired only by experience.

If any apparatus is to be carried it is generally tied to the string below the kite or kites after the latter are in good flight and produce a steady and sufficient strain on the string.

The tension on the string varies greatly when only one kite is flying, owing to the tumultuous and ever changing character of the wind. These variations are very much less with two kites in tandem 200 or 300 feet apart. With a tandem of several kites the strain is naturally still more nearly constant.

The manner of flying kites in tandem is also very simple. The kite to be added is first flown on an independent string. A length of from 100 to 150 feet is generally sufficient. The end of this is tied to the main kite line at the desired point. The kite takes care of itself as string is paid out, although in some cases from time to time during its subsequent flight it may foul partly and temporarily with the main line. If there are no points or projections on the second kite that can be permanently caught on the main line, then the fouled kite will generally soon free itself. It ought to ride above the main line except during momentary lulls of the

wind, and often owing to its own lack of perfect symmetry and exact correspondence with other kites or to variations of the wind, it will continuously tend to fly to the right or left. Thus several causes are seen to conspire which tend to make the kite stand free of the main line. There is always, however, in tandem flying, more or less wasted effort in the kites pulling at variance with each other. This will be discussed later.

The work done at the Weather Bureau by Mr. Potter in flying kites prior to the beginning of the investigations by the writer, consisted principally of tests of the Malay or Eddy kite. Although this form of kite is well known a brief description will remove any uncertainty respecting its construction. The frame consists of two sticks of the dimensions shown in Fig. 1. At the point of crossing the sticks are lashed firmly together with waxed string. The cross stick $A B$ is bowed backward by means of a string, as shown in the end view, Fig. 2. The depth of the arch is best made about $\frac{1}{10}$ of the arc. A strong cord, $A C B D$, is passed around the frame and securely fastened to the ends of the sticks, so as to produce a perfectly symmetrical figure. The woven wire cord used for hanging pictures, which will not stretch, is much better than any kind of string for this purpose. Paper, calico, cambric, or silk may be used for the covering, which is allowed to bag slightly in order to improve the stability of the kite. The bridle is formed of a piece of stout cord whose ends are tied, respectively, to the point on $C D$ at which the sticks cross and to a point near the end, D. The length of string should be such that when the bridle is drawn taut and laid over against the surface of the kite it will form the angle $O B D$, Fig. 1. The kite string is attached to the bridle by means of a weaver's knot near the point B. The exact position for the best effect can be found only by trial. Mr. Potter sought to improve upon this form of kite by substituting for the bowed cross stick two sticks set so as to form a slight dihedral angle, the effect being to impart a greater degree of stability. With the object of providing a degree of flexibility to the wings of the kite for the purpose of easing off the strains due to gusts of wind, Mr. Potter tried connecting the two cross sticks of a dihedral angle kite by means of a spring. He also inserted a spring of rubber bands in the bridle at D, expecting thereby that the after part of the kite would tip up so as to partly spill the wind and ease off the strain of heavy gusts. These attempts to compensate for the gusty character of ordinary winds met with but indifferent success, doubtless owing to the difficulty not only of securing the proper proportions between the strength of the springs and the surface of the kite, but of arranging that the spring should bend or elongate the right amount for a given variation of the total strain. To be effectual it is plain that springs for the above-mentioned purpose must be nicely gauged for both the total strain they must sustain and the flexture or elongation per unit strain.

Two sizes of cable-laid twine were used by Mr. Potter, namely,

a heavy twine, $\frac{1}{10}$ of an inch in diameter, weighing about 3.75 pounds per 1,000 feet, and a lighter twine, 0.065 of an inch in diameter, weighing about 1.2 pounds per 1,000 feet. The cord was wound upon a large reel or flanged drum, about 18 inches in diameter. The box within which this drum revolved was firmly bolted to a low table with circular top, but in such a fashion that the box could at any time be revolved in azimuth upon the table top, so as to bring the reel in the proper azimuth according to the direction of the wind. The legs of the table were firmly anchored to the ground. (See further description, page 24.)

These appliances were installed at Mr. Potter's country residence near Washington. The exposure was exceptionally free from obstructions and in many respects very favorable for kite experiments.

When the writer began his investigations of the kite problem in December, 1895, he therefore found much of the necessary apparatus in readiness, and he takes this opportunity to testify to Mr. Potter's skill and experience, and his ability and ingenuity in designing and constructing kites. As will appear in the following pages, Mr. Potter proposed and constructed two or three modified forms of kites, each of which possessed more or less merit, and he had already been successful with the Hargrave kite.

The foregoing brief account sets forth the principal features of the status of the kite work of the Weather Bureau at the time the writer was directed by Professor Moore to investigate the problem of securing meteorological observations in the upper air. What follows aims to set forth the progress made up to July 1, 1896, in developing the kite.

As has already been said the construction and flying of kites on a large scale is purely and only an engineering problem. It is simply a question of stresses and strains, the strength and resistance of materials; a question of the operation and equilibrium of certain well-defined forces. These ideas have been constantly in mind in my efforts to improve and apply the kite to meteorological purposes. The results presented below aim to follow in some sort of logical sequence. Naturally the actual chronological succession of the experiments was often illogical and the results fragmentary in character.

The position a kite takes when poised in mid-air is the result of a condition of equilibrium of five different and wholly independent forces: these are: (1) The pressure of the wind on the kite surfaces. In this I mean to include every wind force whatever, whether exerted upon the extended sustaining surfaces or upon the relatively small ends, sides, edges of the sticks and framework of the kite, the edges of the cloth, wire ties, etc. The skin friction of the wind gliding over the surfaces, if considered, is to be included here also. The resolution of this composite force into its several components and the analysis of their separate effects is a question in itself.

(2) The attraction of gravity for the kite. (3) The tension of the string at the kite, that is the restraining pull of the line. (4) The attraction of gravity for the string. (5) The pressure of the wind against the string.

Kite strings.—Inasmuch as the first requisites for kite flying on any extended scale are a convenient reel and plenty of string or line of adequate strength and quality to hold the kites, it will be appropriate to first dispose of some exceedingly important questions relating to the string.

The properties of most importance in determining the fitness of a given material for kite strings are (1) strength, (2) weight, and (3) diameter of the cord, that is, the amount of surface exposed to the pressure of the wind. Generally this last factor—the action of the wind on the string—has been quite ignored or, what is worse, if considered, has been regarded as too small to be of any importance. Such is far from being the case, especially in lofty flights, in which case we must deal with thousands of feet of line.

The size of string generally used in flying kites tandem measures at least one-tenth of an inch in diameter. The area of the longitudinal section of such a string equals a square foot of surface for each 120 feet of running length, that is to say, 44 square feet of surface to the mile. Even though the exterior surface of the string has a rounded form, yet the length we are obliged to deal with in a given case is so great, and a great portion of the string is set at so steep an angle across the direction of the wind, that we must not for a moment assume that the wind pressure on all this surface is too small to be worth considering or that the string can escape being depressed toward the earth by the wind to a very considerable extent. Every one perceives with the eye the very great effects that gravity is able to produce on a long piece of even very fine string, and we all know how great the tension must be to stretch a long piece of string until it is even approximately straight. The actual disturbing force of gravity in operation in such cases is a very feeble one; much feebler, indeed, than the pressure the wind may exert on the same string. If one is skeptical of this statement let him try the following simple but crucial experiment: Take several feet of gilling thread, or similar fine string, such as would be used for flying small kites. Suspend this in a slack loop with the ends on about the same level. If no wind is blowing, the loop will hang in a vertical plane. If, however, the string be suspended where freely exposed to the wind and so that the loop hangs directly across the direction in which the wind blows, the loop will no longer hang in a vertical plane, but will be blown strongly to one side and assume a steeply-inclined position. In fact, with string as light and fine as gilling thread the loop will be blown out quite horizontally with only a gentle breeze. In this experiment the wind and the force of gravity are the only external forces, aside from the reactions at the fixed supports, which affect the position

of the string. The wind acts horizontally, gravity acts vertically, and the loop of string takes an inclined position intermediate between the horizontal and vertical. If the two forces are equal, the plane of the loop will be inclined 45° to the horizontal. The observed fact that the string, in many cases, is forced by even moderate winds to a much higher angle than 45° is very significant. It means that the pressure of the wind on each elementary portion of the string is much greater than the weight of an equal portion of the string. The fact that the string in the loop is under very feeble tension, whereas a kite string is under great tension, does not in the least alter the fact that the pressure of the wind on the string is equal to or greater than the attraction of gravity. Furthermore, the fact that the kite string hangs in the direction of the wind, instead of across it, can not annul the effect of the wind, which in such a case is superimposed upon the effect due to gravity, and quite escapes detection by simple methods. In fact, the effect we observe with the eye is commonly regarded as due to gravity alone, whereas it is really the effect of both gravity and the wind. The thoughtful investigator will derive a valuable lesson from a few experiments of the above-described sort with strings of different sizes.

Enough has been said to show that in selecting a kite string the *diameter* of the string may be of even greater importance than its weight.

The judicious selection of the kite string and the adoption of correct methods for uniting its different portions, or for attaching it to the kite, are impossible without a complete knowledge of the strength of the string itself, and of the knots, splices, and other junctions employed.

The testing apparatus described below was hastily improvised for service in the Weather Bureau work, but proves so simple and useful that others may wish to make and employ a similar one in their own work.

Two pieces of square steel, *A*, *B*, Fig. 3, driven through round holes in a flat bar of iron, convert the 4-foot bar into a powerful lever with the knife-edge at *A* for a fulcrum, and the edge at *B* for applying the force. The bent pieces of flat iron, *C*, *D*, form at once the stirrup for transmitting the strain from the knife-edge, *B*, and the jaws within which one end of the string or wire to be tested is grasped. The clamping of the jaws is effected by means of a small independent steel screw-clamp. These latter may be procured from dealers in hardware or tools generally. The support for the lever is most conveniently made of a stick of wood of the form shown and adapted to be attached when required to the side of a bench in such a manner that the long arm of the lever passes obliquely over the top of the bench. The knife-edge, *A*, is arranged to be supported on suitable metal surfaces at the top of the stick. At about 24 inches below the end, *B*, of the lever, a projection is formed in the board. Two iron blocks, *E*, *F*, provided with steady-pins and a clamp, constitute the

jaws for grasping the remaining end of a string or wire to be tested. The edge of the projection at G has formed within it a narrow slot or rabbet through which the string may pass, while the plates, E, F, of the clamp abut against the lower face of the projection. This arrangement admits of testing specimens of considerable length. The necessary strain for breaking a specimen is easily produced by hanging any heavy weight upon the long arm of the lever. I have employed, for convenience, one of the Fairbank's 50-pound standard weights. In order to graduate the lever-arm so as to indicate the strain on the specimen in pounds, a rude wooden scale-pan was suspended from the clamp, C D, into which was placed objects of known weight up to about 150 pounds, due allowance being made for the pan. From the several positions of the sliding weight, when just balancing the known weights, the complete system of graduation for the lever is accurately determined. By this device strains of something like 350 pounds can be produced upon specimens to be tested. This is quite sufficient for kite work. Tests of the strength of strings, wires, knots, splices, etc., as given hereafter, were all determined by means of the device described above.

To grasp a specimen so that it shall not slip nor yet be impaired in strength, did not prove to be very difficult. The jaws of the clamps are comparatively smooth. To increase the holding of these they were occasionally rubbed with powdered resin. For testing hardened steel pianoforte wires it was necessary in addition to rub the ends of the wire itself with powdered resin, also to form a kink in the extreme ends of the wire and grasp the wire in such a manner that these kinks draw into the sharp angle formed by the slightly divergent jaws of the clamp at one end. With these expedients for grasping the wire excessive clamping was not necessary, and only occasionally would specimens break at the edge of or slightly within the jaws.

The following table contains information respecting the properties of materials that may be employed for kite strings:

TABLE I.—*Properties of materials for kite strings.*

Kind of string or wire.	Diameter.	Weight per 1,000 feet.	Breaking strength.	Relative surface exposed to wind; sq. in., per foot.
	Inch.	*Lbs.*	*Lbs.*	
No. 12 gilling thread	0.032	0.25	30	0.38
Cable-laid twine	0.065	1.20	62	0.78
Do	0.100	3.8	160	1.2
Do	0.150	7.1	300	1.8
Phosphor-bronze wire	0.028	2.5	80	0.34
Aluminum wire	0.0477	*2.15	*48	0.57
Steel piano wire	0.028	2.15	200	0.34

*Computed from general tables; not directly tested.

Tests of silk strings of suitable size for kites would form a valuable addition to this table, but specimens were not available.

From the table we see that aluminum, which many mistakenly regard as a peculiarly useful metal for almost every purpose, is, in fact, the worst material of all for a kite string. It is not only very much heavier, but thicker and more easily broken than fine cable-laid twine. On the other hand steel pianoforte wire is by far the strongest for the same weight and the most slender of any of the materials tested. The tendency of metallic wire of any kind to kink and give trouble on that account if employed for flying kites is by no means serious and the little extra pains required to prevent kinks and rusting, in the case of steel, is well repaid in the great superiority of steel in every particular. The writer at once substituted wire for string in December, 1895, and its admirable fitness for the purpose is abundantly confirmed by extended experience.

The steel piano wire selected for the Weather Bureau work measured about 0.028 of an inch in diameter. This is the size generally employed for deep-sea sounding purposes. In the use of wire a question of first importance is, how shall it be spliced? In my early work the wire was spliced according to the recommendations of authorities on deep-sea sounding. Disastrous results ensued from the parting of the wire in the splices. Thereupon a thorough investigation of the strength of splices was made by means of which a form of splice was evolved that it has been impossible to break. The single wire either side of the splice will always break first. Fig. 4 shows a common form of soldered splice, recommended and used for splicing wire employed in deep-sea sounding. This is a bad form of splice and will, in almost every case, break in the middle and at a less strain than required to break the wire. The only part of the splice that is at all effectual in resisting strain is the short intertwisted portion in the middle. It is plain that throughout the whole portion, *a*, *b*, where one wire is coiled closely around the other which remains straight, practically the whole strain is carried, and necessarily must be almost wholly carried by the straight core wire. The solder of the splice can carry only a little of the strain. The coiled wire in the portion, *a*, *b*, is, therefore, so much wasted material. The mechanical principles involved in splicing a wire by twisting requires *that each part be twisted around a common axis.* It is wrong to twist one part wholly around the other which remains straight. According to this principle the splice shown in Fig. 4 is evolved into the splice shown in Fig. 5 by discarding the portion *a*, *b*, and elongating the middle portion. Although not necessary for strength it will generally be well to take one turn of the wire around the main part at each end of the splice and taper down the point somewhat by filing. This will lessen the danger of damaging the splice in

case it drags across the edge of the reel or some rough hard object, and the splice will perhaps pass more easily through the hand or through oily cloths which must sometimes be employed to prevent rusting. In not a single case have soldered splices of this formation ranging from 2 to $2\frac{1}{2}$ inches, extreme length, been broken. Fifteen specimen splices were tested. The wire outside of the splice was broken in every case at average strains of about 225 pounds. Minimum strength, 210 pounds; maximum strength, 235 pounds. The solder may be applied to the splice with an ordinary soldering iron, treating the splice first with soldering acid in the usual way. A better plan[1] is to submerge the splice in a small quantity of molten solder contained in a shallow groove in a block of wood. By this method there is little danger of overheating the wire and impairing its temper. Those familiar with soldering need not be told that the completed splice must be thoroughly washed with clean or alkaline water so that every trace of the soldering acid is removed, otherwise excessive rusting of the wire will quickly ensue. Keeping the wire thoroughly coated with a film of oil has thus far been sufficient to prevent rusting. The wire has, however, never been exposed much to rain and damp.

Inasmuch as the security and strength of the splice described above depends upon *the wires being evenly and uniformly twisted each about a common axis*, the twisting is best effected by using simple tools, such as shown in Figs. 6 and 7. The wires to be spliced are clamped in the small block of brass, *A*, having two shallow converging saw cuts as indicated by the dotted lines. The block is fitted with a brass plate covering the slots and kept in position by steady pins, *a*, *a*. The cover plate is made to clamp the wire in the shallow slots by means of a common machinist's hand vise, not shown. The brass block, *B*, also cut with slots converging the same as in *A*, serves for twisting the wires. The cover on the block, *B*, simply confines the wires to the slots without clamping them. Rotating the block, *B*, on its longitudinal axis twists the wires as evenly as can be desired. If the free ends of the wire are to be turned once closely around the main wire, this is effected by means of a tool shown in Fig. 7, which scarcely needs explanation. The splice is finished by nipping off the extreme free ends of the wires close down to the main wire and, if desired, the ends may be further touched up, before soldering, by careful filing to the form shown in Fig. 5.

While steel wire is the best material for the kite line, yet it is not convenient to form a continuous wire connection up to the kite, especially during the experimental stage of the work when alterations in the points and manner of attaching the wire to the kite are necessary. String is peculiarly adapted

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[1] Described in Deep-Sea Sounding and Dredging, Sigsbee. U. S. Coast and Geodetic Survey, 1880.

for such connecting purposes, on account of its flexibility and the facility with which it can be tied in knots. Twine of suitable strength has, therefore, been employed for the bridles of the kites. To the bridle is also attached a short length (from 4 to 6 feet) of twine which will hereafter be designated the "stray line." By this arrangement of bridle and stray line any desired adjustment and alteration of the bridle attachment may be made by means of knots hereafter to be described. The stray line provides means for readily attaching a kite to, or detaching it from, the wire, still preserving any desired bridle adjustment.

Correct engineering practice requires that we inform ourselves definitely concerning the strength of every important member of a structure. Therefore, when we employ string in the bridles and the stray lines of our kites we must definitely ascertain their strength, especially if tied and knotted together.

The question as to how well and conveniently knots answer their purpose, and to what degree they constitute a weak spot in the string containing them, is a very interesting one for investigation. Although string is used in the Weather Bureau work in only a subordinate capacity, yet a number of tests of strings united by different kinds of knots were made, and as the results may prove useful to those who employ string instead of wire for flying kites they are given in the table below. All the tests were made on new cord that had never been used. The cord was a hard twisted cable-laid twine, which measured between 0.105 and 0.115 of an inch in diameter and weighed in the slack cord 4.1 lbs. per 1,000 feet.

TABLE II.—*Strengths of cords united by various knots.*

No. of test.	Kind.									
	1	2	3	4	5	6	7	8	9	10
	Double overhand knot.	Sheet bend or weavers' knot.	Sheet bend, double turn.	Square knot.	Fisherman's knot.	Interlaced overhand knot.	Interlaced figure of 8 knot.	Carrick's bend.	Bowline bend.	Cord unknotted.
1	110	118	160	158	172	143	185	179	172	171
2	138	127	110	174	173	156	138	175	187	180
3	150	118	146	158	154	145	149	175	193	165
4	120	125	160	110	140	174	160	161	178	167
5	135	112	131	138	133	171	150	182	165	169
6	......	......	......	168	......	......	140	......	191	182
7	......	......	......	163	......	......	162	......	198	172
8	......	......	......	143	......	......	170	......	202	160
9	......	......	......	......	......	......	150	......	190	194
10	......	......	......	......	......	......	135	......	185	198

The exact structure of the knots will be understood from the illustrations, Figs. 8 to 16. The so-called "double overhand knot" was tested because it is so commonly used by a novice for uniting two strings, and because it has often been employed in flying kites tandem for the purpose of forming a

loop in the main line, as shown at *a*, Fig. 8. It is a very bad knot for the purpose. The "weavers' knot" or "sheet bend" is very small and compact, but cuts upon itself badly and is weak. The "square knot" is much better, but is not always proof against slipping a little, which, if it occurs under considerable strain is almost certain to result in a break at the knot. The tendency to slip is almost wholly removed by drawing the parts taut in such form that the loose ends stand well out at an angle to the main parts. Do not tighten up the knot while the loose ends are held parallel with the main parts. Fig. 11 shows the knot correctly tied.

It seems there may be some difference in the strength depending upon whether a knot is tied *with* or *against* the "lay" of the cord. I have not, however, been able to definitely discover a difference of this sort.

The "fisherman's knot"[1] called also "surgeon's knot" by Eddy and Fergusson of Blue Hill, is compact and comparatively strong. The "interlaced overhand knot" is formed by tying a simple knot loosely on the end of one string and passing the end of the other string through and around the knot in the opposite sense, as shown in Fig. 13. The "interlaced figure of 8 knot" is formed in a precisely similar manner, based on the knot shown in Fig. 14. Each of the foregoing knots draws down exceedingly compact and hard, and it is almost impossible to untie them after being strained, especially the two latter. This is also true of the "Carrick's bend." The latter, however, is designed to unite heavy ropes, hawsers, etc., and in such cases the loose ends of the knot are "stopped" or lashed to the main parts, and in such condition the knot can not jam. Occasionally the knots enumerated from 1 to 8 in the table will sustain a strain that will break the cord, but such was found to be rather the exception and generally the string appeared to break at a weak point.

The king of all the knots, however, is the "bowline knot," not only because of its remarkable strength, which is such that the cord itself will break at a high strain while the knot holds in the majority of cases, but from the adaptability of the knot to a variety of purposes and from the fact that it never slips and can be untied with the least possible effort, even after sustaining excessive strains. Fig. 16 shows the manner of uniting cords by this knot, and although for this purpose it is less compact and neat than other knots, it is exceedingly trustworthy and can be depended upon to nearly or quite the full strength of the cord. It has no equal for uniting two cords differing in size. It will never break at the point, *a*, which I was at first inclined to regard as a weak spot. This knot is so excellent that its use is strongly recommended. The successive steps in a simple manner of tying it will be given, as the beginner may find some difficulty in forming the knot easily with no other guide than Fig. 16. The first step

[1] Chamber's Encyclopedia. New edition, New York, 1892.

is to form a simple overhand knot, held as shown in Fig. 17; by a dexterous turn of the fingers the knot is brought to the form shown in Fig. 18, and finished by passing the end behind the main part and through the eye, as shown in Fig. 16. The act of tying the knot is one continuous motion. In drawing the knot taut it is not necessary or desirable to tighten up the crown (*a*, Fig. 16,) of the knot very much. To untie the knot the crown is first drawn over in a manner to free the knot, whereupon the whole is easily undone.

As already mentioned, when wire is used as the kite line, string need be employed only for bridles, stray lines, and other short connectors. The end of the wire is formed into a small eye which incloses an eyelet, as shown in Fig. 19. The string from the kite is attached to this eyelet by means of a bowline knot. A number of actual tests demonstrated the superiority of this knot for forming this junction.

While discussing knots it will be well to dispose of the matter and describe the manner of tying the bridle to the kite sticks and of adjustably attaching the stray lines to the bridle.

Fig. 20 illustrates both these connections. The clove-hitch reinforced by one or two half hitches of the loose end of the string around the main part of the bridle seems to answer every purpose for securing the bridle to the kite stick. I have been unable to discover a more excellent method of attaching the stray line to the bridle than by means of a bowline knot, the loop of which forms with the bridle a square knot, *a*, Fig. 20. The knot cannot slip in use and even if excessively strained it can be loosened with the slightest effort and in such a manner that the point of attachment can be easily shifted by any definite and precise amount. The simplest way of forming the square knot between the loop of the bowline and the bridle is to tie the bowline first, independent of the bridle, then pass the loop of the bowline around the bridle and draw the end of the stray line, which will generally be free, through the loop of the bowline, forming the knot shown in Fig. 21. This is easily converted into the square knot shown in Fig. 20. The complete arrangements of bridle and stray line was repeatedly tested with the result that the arrangement was fully as strong at every part as the cord itself.

It still remains to describe what methods have been developed for attaching kites in tandem. Where string is employed for the kite line a simple loop knot, *a*, Fig. 8, may be formed at any point desired. As already pointed out, and as shown in Table II, if this knot is tied in the manner figured, the strength of the line is thereby weakened in a very serious manner. As it is plainly very bad practice to impair the strength of hundreds of feet of strong cord simply by one or more weak knots, it is also plain that those who employ string for the kite line need a method much better than that just described for forming a loop or other device by which the following kites of a tandem may be attached to the main

line. The importance of this little matter is still more apparent when we consider that if a single one of these knots or loops forms a point in the line which is 33 per cent weaker than the weakest place in the cord itself, a condition which the tests show is easily possible, then to safely sustain a given strain the entire length of line involved must be 33 per cent stronger, that is, approximately 33 per cent heavier than would be required if the strength of the cord was not thus impaired by loops. The weight and size of the string are of such vital importance in flying kites to extremely great elevations that bad practice of the kind just pointed out can not for a moment be tolerated.

The foregoing remarks apply equally in determining what arrangements will be admissible for attaching tandem kites to wire. Every device that impairs the normal strength of the wire must be ruled out. In speaking of the several kites forming a tandem it will be convenient to designate the top kite as the leader, or pilot, kite. The others may be called subordinate kites or followers, and the line of wire leading up from the reel will be called the main wire, or main line, while the relatively short branches leading up to the subordinate kites will be spoken of as secondary lines.

An angle in the continuity of the main line is formed at any point at which a secondary line is attached. This angle varies from moment to moment with the ever changing wind forces on the different kites. If wire is used and flexibility is not provided for at the point of attachment, or other means adopted to obviate ill effects from bending, then it is only a question of time before the strength of the wire will be impaired. The writer has not been able to conceive of a clamp for this purpose that is entirely free from serious objections. After discarding loops of string firmly lashed with waxed twine to the wire he has, however, adopted the eyelet arrangement shown in Fig. 22. In addition to forming a perfectly flexible point of attachment, the strength of the junction, with double twisted wires either side of the eyelet, is stronger than the wire itself, as shown by actual tests.

Steel wire of the same size as the main kite wire is also employed for the secondary lines. The length ranges from 100 to 150 feet, with an eyelet in each end, as shown in Fig. 19.

The connection of the secondary line to the intermediate eyelet of the main line is made by a short piece of twine tied to the eyelets by means of the bowline knot.

The intermediate eyelets put into the main line are too small to present any difficulty in stowing away upon the reel. The only objection to them hitherto found is that the points at which attachment to the main line is possible are fixed and predetermined, and can not be chosen, as is sometimes desired.

The relative merits of several small kites flown tandem as contrasted with spreading the same amount of surface in one or two large kites, will be analytically discussed

later. It may be stated here, however, that although the tension on the line becomes more and more steady the greater the number of kites in tandem, yet the gain in steadiness when more than two or three kites are employed is entirely unimportant, and, as will be shown hereafter, a large kite is more effective than an equal surface in small kites flown tandem. Based on these considerations the practice at the Weather Bureau has been to fly but a small number of kites tandem, and the use of eyelets at fixed points in the main wire has been generally satisfactory.

One further difficulty has presented itself in the use of wire, and for which thus far no satisfactory solution has been reached, namely; if the wire is in a state of internal strain, such that when stretched it tends to rotate on its longitudinal axis (and if no provision of a swivel or other device has been made for relieving this twisting strain), then under certain conditions of moderate strain, and at moments when the main and a secondary line take nearly coincident directions, the two may intertwist around each other for a length of many inches, but be again violently untwisted more or less completely when a condition of stronger winds and heavier strains prevail. It is needless to say that such action threatens to impair the strength of the line.

Swivels are believed to be of no avail to obviate this difficulty. In the first place they must be capable of resisting a strain at least as great as the ultimate strength of the wire. Made in the ordinary way the friction, owing to heavy strains that would occur in use, would wholly prevent their effectual action. A ball-bearing swivel would, we believe, not be much better. Moreover, even supposing an effective swivel available, as rotation of the kite wire can not take place across the angle formed at the point of attachment of a subordinate kite of a tandem, it would be necessary to provide a swivel at each point of attachment of a secondary line. The winding of bulky ball-bearing swivels on the reel presents a serious objection to their introduction.

From the foregoing statements and data respecting the materials and arrangements which form the kite line, it will be seen that the maximum of strength with the minimum of weight and surface exposed to wind action is approximately attained by the use of steel wire. With the arrangements recommended, there will be a uniform strength throughout, with no inherently weak points of construction nor portions of unnecessary strength, and, therefore, unnecessary weight. The main wire is expected to withstand the united pull of several kites, and must, therefore, be stronger than the bridles, stray lines, etc. These latter, when made of the cable-laid twine employed in making the tests given in Table II, are, as shown therein, stronger in proportion to the strains they must sustain than the wire itself. The excess of material and weight involved in this excess of strength is very small, however, and of no import-

ance. For small-sized kites smaller twine may be safely employed.

The following table contains the results of tests upon splices, eyelets, and other members that go to form the line by which a kite or tandem of kites is anchored to the earth:

TABLE III.—*Ultimate breaking strength of members of kite line.*

Number of test.	Steel wire.	Marvin splice.	Eyelet, Fig. 19.	String tied in eyelet, Fig. 19.	Stray line and bridle.
	Lbs.	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*
1	229	225	206	207	184
2	220	210	216	185	194
3	219	225	....	170	188
4	250	228	....	181	198
5	223	223	....	183	184
6	213	225	....	181	194
7	220	229	....	....	161
8	....	229	....	....	191
9	....	210	....	....	201
10	....	226	....	....	202
11	....	225	....	....	205
12	....	233	....	....	200
13	....	233	....	....	194
14	....	231	....	....	207
15	....	231	....	....	194

The reel.—The reel required for the proper management of either the kite wire or string will need little or no description, except in respect to particular adaptations, and especially in regard to the means employed for measuring the total length of the wire or string and the length paid out to the kite at any time.

It will frequently be necessary, when flying kites in light winds, to keep the kite afloat by reeling in the wire more or less rapidly. For this purpose experience has shown that the circumference of the drum of wire or string should be scarcely less than 5 feet. A much larger drum than this, where it is to be operated by hand, will prove difficult or, at least, inconvenient to manage when the wire is under considerable strain. Moreover, it is desirable to avoid the use of multiplying gear, such as would be required with very large drums in order to secure adequate power for the purpose of winding in kites by hand when exerting strong pulls. A drum 18 inches in diameter operated by two hand cranks, each 15 inches long, represents something over a threefold reduction, which in the large majority of cases will prove ample.

A very interesting phenomenon connected with flying kites with wire is the electrification of the wire. To be able to observe effects of this sort, it is necessary that the reel of wire be insulated, which is accomplished satisfactorily if the drum is made of heavily shellacked wood. The core of the drum must be made very strong, to avoid the enormous crushing pressure incident to winding in turn after turn of the wire under heavy strain. For the same reason the flanges must be com-

paratively thick, to prevent flexure, and strongly riveted to the core, to prevent being forced asunder.

Fig. 23 shows the second reel employed in the Weather Bureau work. Our first reel was only 12 inches in diameter, and proved to be too small, and the flanges were too weak. About 10,000 feet of wire forms a layer on the large reel a little over 0.4 of an inch deep.

The inside end of the wire on the reel comes through the flange to the button, *a*, which can be electrically connected to the earth by the switch, *A*.

For the purpose of indicating the number of rotations made by the reel the axis is provided with a suitable worm, arranged to actuate the dial mechanism of an ordinary anemometer. The length of wire corresponding to any particular dial reading is obtained by means of a numerical table, the computation of which will be explained later.

The carriage upon which this reel is mounted is shown in Fig. 24. It is the same carriage employed by Mr. Potter in his work with string. A central bolt confines the box, *A*, to the low table, *T*, but permits rotation thereon, aided further by castors near the four corners.

The rope brake, *b*, Fig. 24, which passes almost completely around the reel in a friction score, or groove, of the flange, serves perfectly to control the rapid paying out of wire, the necessary restraint being produced by tightening gently the slack end of the rope at *c*. The reel being of wood, and, therefore, but a poor conductor of heat, temperatures sufficient to scorch the rope and wood in the groove have sometimes resulted from the great friction, but no serious difficulty has been experienced on this account.

When wire is paying out under control of the brake the rapid rotation of the hand cranks is somewhat objectionable. To provide them with ratchet connections so that they may remain stationary when the reel is unwinding, as is done in some forms of reels for deep-sea sounding purpose, is not altogether desirable in kite work, as the strain on the wire is sometimes exceedingly variable. Moreover, a rigid handle is most trustworthy in cases where it is necessary to control the reel by the handle for both winding and unwinding.

A common and well known form of spring balance has been generally employed to ascertain the tension produced by the kites. One method has been to hook the dynamometer directly to one of the crank handles, fixing it in such a position that the restraint is exerted in a direction closely at right angles to the crank arm. This method, which is preferred from the fact that the reel can be quickly disengaged from any restraint should emergency demand, requires that a reduction factor be applied to the observed dynamometer reading, depending upon the ratio between the crank arm and drum radius at the point from which the wire draws. The ratio is always known for any given length of wire out, so that the reduction presents no difficulty.

A second method, which measures the tension directly, consists in arranging the dynamometer to draw over the surface of the drum itself by means of a cord wound partly over the outer layers of wire, as shown at Fig. 25.

When reeling in distant kites the wire is guided wholly by shifting the carriage of the reel slightly in azimuth, as may be required from time to time. We have found the direction of the wire to remain so nearly constant that this means of control is ample, and it further avoids any necessity of touching the wire with the hands, which is liable to induce rust. Near the close of the operation, when the kites are but 100 or 200 feet distant, it may be necessary to guide the wire by hand. As a precaution against rust, the wire in reeling in is sometimes oiled by causing it to draw through a piece of folded cloth held in the hand and saturated with oil.

The evaluation of the readings of the dial showing the number of revolutions of the reel is effected once for all by accurately measuring in sections a long length of wire as it is wound upon the reel. In the case of the reel under discussion the length of wire was measured by causing it to pass around a disk having a known circumference and which revolved with the greatest freedom. The disk, in fact, was mounted upon the spindle of an anemometer, the dial readings of which indicated the number of turns of the disk. The tension of the wire was regulated by causing it to pass between a friction plate of wood so arranged as to guide the wire in its passage to and from the measuring disk and at the same time prevent any slipping or shifting of the wire on the grooved periphery of the disk. The apparatus is shown diagrammatically in Fig. 26. The observations for the measurement of the wire are of the following nature: The end of the wire being passed around the disk and secured to the reel, note is made of the dial readings to the nearest tenth of a revolution of the disk and reel, respectively. Approximate chalk mark subdivisions answer for the fractions of revolutions. When fifty turns of wire are wound on the reel, readings of the dials are again noted, and so on. In addition to noting the readings for each fifty turns of the wire, readings are also recorded at the end of each full layer. In winding the wire on the reel, originally, it is not difficult to lay it on very evenly for a depth of seven or eight layers, but splices and other irregularities break up smooth winding, and after a time definite layers cannot be formed. It is impracticable, however, to guide the wire in even layers when reeling in kites. By a preliminary weighing of several of the sections of wire wound on, and by accurate determination of their respective weights per unit length obtained by measuring and weighing short samples, the above-described series of observation may be made to suffice first, for determining the exact periphery of the measuring disk and then the length of wire corresponding to any number of turns of the reel. In this case it will of course be neces-

sary (*a*) to note the dial readings at the times the splices between sections pass on to the reel, and (*b*) to make slight corrections for the few inches of the wire used in forming the splices.

To show what variation may be expected in different portions of wire, nominally of the same size, and to present data from which an idea of the accuracy attained in measuring the length of the wire by the above-described means, the following observations are quoted:

TABLE IV.—*Weight per unit length of samples of steel music wire. Nominal diameter of wire,* 0.028 *inch.*

Sample.	Length.	Weight.	Weight per foot.	Whole coil. Weight.	Whole coil. Length.	Periphery of disk.
	Feet.	*Grms.*	*Grms.*	*Grms.*	*Feet.*	*Feet.*
1	27.335	27.343	1.0003	1248.9	1251.0	3.1511
2	18.445	18.370	.9959	2240.0	2244.0	3.1558
3	23.057	21.966	.9527	2241.0	2335.2	3.1433
4	12.396	11.956	.9666			
5	29.989	28.996	.9666	2286.2	2368.6	3.1700
6	11.696	11.272	.9637			
7	30.703	29.618	.9647	2239.3	2316.7	3.1502
8	12.034	11.655	.9685			

Mean periphery, 3.1541.

NOTE.—Samples joined by brackets were cut from outer and inner ends of the same coil.

A layer of wire on the large reel contained, on the average, about 155 turns. All the observations in a single layer were combined as an average for that layer. The law of increase of the periphery of the reel, with successive layers of wire is practically a linear law. A ready and sufficiently exact solution of the observation equations is therefore obtained by aid of a diagram. The table below contains the results for the large reel.

TABLE V.—*Observed and computed length of wire of large reel.*

Layer.	Turns of reel.	Total length by measuring disk.	Tabulated length.	Difference, obs. — table.	
		Feet.	*Feet.*	*Feet.*	
*	31	151.5	151.4	+ 0.1	* Outside fractional layer.
...	331	1,614.7	1,614.0	+ 0.7	The extreme outside layers were not distinguishable in the observations.
13	481	2,342.3	2,342.0	+ 0.3	
12	631	3,067.7	3,067.8	− 0.1	
11	743	3,608.2	3,608.2	0.0	
10	931	4,512.6	4,513.0	− 0.4	
9	1,092	5,284.5	5,285.2	− 0.7	
8	1,244	6,011.0	6,011.8	− 0.8	From the eighth layer, to and including the first the winding is in smooth layers.
7	1,395	6,731.8	6,731.5	+ 0.3	
6	1,547	7,454.0	7,453.7	+ 0.3	
5	1,696	8,159.6	8,159.6	0.0	
4	1,831	8,797.8	8,797.2	+ 0.6	
3	2,011	9,647.0	9,644.8	+ 2.2	
2	2,170	10,394.7	10,390.9	+ 3.8	
1	2,331	11,146.6	11,144.1	+ 2.5	

There is doubtless a slight difference in the average length per revolution depending on whether the wire is wound in smooth layers or not, but I have been unable to definitely evaluate any difference of this sort, notwithstanding that what I may call the calibration measurements agree and harmonize among themselves with considerable precision. Moreover, in using the wire, several thousand feet may be unwound from smooth layers and wound on irregularly, and it will be found the dials come back to the starting point very satisfactorily. Differences of a fraction of one per cent may be due to differences of tension.

Thus far the manner of using steel wire for the kite line has been described and the results of experiments given, showing the strength and the best arrangement of the wire, splices, string, and other members composing the kite line. The means employed for determining accurately the length of wire unwound from the reel in any case were also given. We will next consider the action of the forces on kites and the form and construction of those with which experiments were made at the Weather Bureau.

General remarks on single plane and cellular kites.—Before the writer began work upon the kite problem many efforts had been made to reach great elevations with kites of the Malay type, the construction of which has already been described. It was often found that these kites would not continue to behave properly hour after hour. When several kites were flying in tandem they would fly very nicely for a time, but a strong gust of wind or the continued action of moderate winds would cause some derangement in one or more of the kites. This would mar the success of the experiment, if it did not bring about some worse result. The real cause of such difficulties was not fully understood at that time. Subsequent experience with other forms of kites has shown how some of the difficulties might have been avoided. The general conclusion, however, is that single-plane kites are believed to be less reliable than kites of the cellular type. The latter are necessarily heavier in construction, but the several sustaining surfaces seem to be disposed in a manner to act with greater efficiency. The cellular or multi-plane kites are also far steadier than single-plane kites, and we believe that they are better adapted than the latter to maintain their equilibrium under great variations of wind force. On the other hand, the single-plane kites, on account of their lightness per unit area, are probably superior to the cellular kites in light winds. Single-plane kites generally prove to be steadier when the covering is fitted loosely, so that it bellies backward with the wind pressure. This looseness, however, is objectionable, for the reason that it is difficult to make the two halves of the kite perfectly symmetrical. The covering, which is generally of cloth, is likely to stretch unevenly with exposure to winds. The kite thereby becomes unsymmetrical, even while in the air, and begins to behave badly. Probably no greater source

of difficulty with single-plane kites exists than the uneven stretching and flexure of the material of the kite. The symmetry of the kite is thus impaired. The ill effects of uneven stretching are greatly aggravated in kites in which the cloth is necessarily cut on the bias, as is noticeably the case in kites of the Malay type. Moreover, a nicer condition of symmetry is necessary in the less stable single-plane kites than in the more stable, steady, cellular forms. In these latter, too, the stretched surfaces of covering material are, as a rule, rectangular in form. Stretching, therefore, is apt to take place in a symmetrical manner and is then attended with little or no ill effect.

From such considerations as these, and the promising results of a few preliminary experiments with a Hargrave kite, the writer was led to adopt the cellular type of kite for further development. He still hopes to be able to determine numerically the efficiency of single-plane kites, as has already been done for the cellular kites, and thereby be better able to judge intelligently of the relative merits of the two forms. As yet, however, the necessary observational data have not been obtained.

ANALYSIS OF FORCES ACTING ON KITES.

Explanation of terms.—The terms *pull*, *lift*, and *drift* are frequently employed in connection with kites, and, as confusion has arisen in the minds of some concerning their use, a full explanation of their meaning appears to be required.

Pull.—The force which tends to tear asunder the kite string is regarded by the writer as the *pull* of the kite, or the *tension* of the string. I do not see that any better or more descriptive words are needed. In the case of a long, deeply sagging line it is plain that the absolute direction in which the pull operates is very different at different points along the line, but always tangent thereto. Moreover, the intensity of the force is also different. We may, nevertheless, with perfect consistency and without confusion, call this force pull or tension at any and every point. To be explicit in speaking of the pull, we need to specify also the point at which the tension is exerted, or the direction in which it acts. We may imagine the kite to be nearly in the zenith and pull the wire upward at a high angle. There is nothing in this circumstance to cause us to change the name of the force under consideration, as has been done by some. The force is just as much as ever the *pull of the kite*, or the *tension of the wire*, no matter at what angle it may act. Such expressions, therefore, as the pull *at the kite* or the tension of the wire *at the reel* seem to me to carry a definite meaning with them.

Lift.—The inherent idea conveyed by the word lift, when used to designate some force, is that of an effort which is opposed to the force of gravity. In other words, a lifting force is an effort which is directed vertically upward. The use of this word in connection with kites will, perhaps, be

made clearer by the following illustration: Suppose the string from a flying kite be tied to a heavy stone. The pull of the kite being exerted in an upwardly inclined direction, the tendency will be to both *lift* the stone off the ground and also to drag it across the surface. That portion of the total pull which tends to raise the stone directly off the ground is the *lift* of the kite.

Drift.—The foregoing illustration serves also to bring out the meaning of the word *drift*, as applied to the kite. That portion of the total pull which tends to drag the stone horizontally across the surface of the ground is called the *drift* of the kite. It is that effect of the total pressure of the wind on the kite which tends to cause the kite to drift horizontally along with the wind. The kite must, however, be held in restraint against the force of the wind, otherwise the drift, as a force, does not exist; if the kite is not restrained, motion sets up and the drift regarded as a force is greatly changed in amount.

In the language of mechanics these words are perfectly defined by saying that *drift* is the horizontal and *lift* the vertical component of the *pull*.

The *lift* of a kite is important for the reason that it measures the amount of weight that the kite can sustain. Weights to be sustained are usually attached to the string. It is a matter of importance at which point along the kite line a given weight to be sustained is attached, for a little study will show that the lift and drift have different values at different points of the line. The more the line sags between any two points the greater will be the differences between the corresponding forces at those points. Fig. 27 represents a long deeply sagging kite line, and will serve to illustrate further the relations between the lift, drift, and pull. At the point *A*, for example, the *pull* is represented by the line *A*, *B*, tangent to the wire. By drawing horizontal and vertical lines through both *A* and *B*, the line *A L* represents the *lift*, the line *A D* the *drift*. Similarly, at *a* the lift and drift are represented by the lines *a l* and *a d*. In this case the line *a b* is made equal to *A B*, that is, the tensions at the two points are regarded as equal. This could not be true in an actual case, as the pull at *a* will always be less than at *A*, depending upon the weight of the portion of wire *a A*. Nevertheless, even though the pull is regarded as uniform in the diagram, the lift and drift are seen to be noticeably different. At *O*, where we have supposed the line to be horizontal the lift has vanished entirely and the drift is numerically equal to the pull. At the reel the lift is no longer a true lifting force; it even acts downward. In other words, the lift is negative. If at any point the kite line were exactly vertical, then the drift would entirely vanish and the lift would be numerically equal to the pull at that point. Such cases will rarely occur as regular working conditions in practical kite flying for scientific purposes. They are noticed

here merely for the sake of illustration. They represent some of the conditions that may temporarily obtain where a long line is out and the wind falls off so much in force that the wire sags down quite to the ground.

The effect of hanging a weight upon the kite string is shown at *W*. The line *W P* represents the magnitude and direction of the pull of the string, *W G* represents the force of gravity. *W P′* is the resultant of these two forces, and the direction the string takes below the point *W* must be identical with *W P′*. Moreover, the length of the line *W P′* represents the tension in the string below *W*.

Resolution and combination of forces.—To proceed intelligently with the construction of kites a general knowledge of the action of the forces thereon is necessary. For our present purpose we will consider kites of the tailless variety only. The position a kite takes in the air will depend upon the resultant effect of five forces acting upon it and the string. So far as the kite itself is concerned we may, however, leave the string out of account and the two forces affecting it, and deal only with the forces acting at the kite. In this case there are three forces: (1) The pressure of the wind on the surfaces of the kite. (2) The action of gravity on the mass of kite.(3) The pull of the string at the kite.

When the kite flies steadily in a fixed position these three forces are in equilibrium. Whenever they are not in equilibrium some one of them preponderates in a certain sense, and the kite shifts its position to the right or left, or rises or falls in such a manner as tends to reestablish equilibrium. That is, a properly made kite will behave in this way. With a kite of improper form and badly arranged parts, no matter how much it darts and shifts about, it is impossible for the kite to move into and stay in a position where the forces just balance each other. The conditions may be such that changes of position do not tend to bring the kite into static equilibrium. The kite, in such cases, may spin around and around in a circle whose diameter is sometimes quite small, but often very great; or, the kite may swing back and forth far to the right and left without finding a position in which it can fly steadily. Such kites, generally, will not continue to fly very long. The oscillations, gyrations, and darting motions which for a time contribute to maintain flight may either gradually bring the kite down lower and lower, or some change in the forces of a marked or critical nature may suddenly end all flight with a precipitate dash to the earth.

Of the three forces in action, gravity alone is perfectly constant in amount and direction. The tension on the string is a force that exists only as the result of the action of the other forces. The wind pressure, then, is the only force which varies independently, and the great problem is to arrange the surfaces and bridle of the kite so that it can promptly, constantly, and easily accommodate itself to the innumerable and often very great and very sudden changes

which we find to occur in the force and direction of the wind.

Wind pressure on plane surface.—The pressure of the wind upon the kite surfaces is a very complex force. We are able to understand its action best by resolving it into component parts and separately studying the effects of each.

In Fig. 28, *A B C D* represents, in cross section, a flat rectangular plate exposed to the wind in an inclined position. The windward and leeward edges of the plate are supposed to be perpendicular to the paper and therefore at right angles to the wind, which is supposed to move in lines parallel to the paper. The thickness of the plate has been purposely exaggerated in order to give prominence to the effect of the wind on the edges of the plate. In kites the edge surfaces are of relatively small extent, but their influence is large enough to be important and it is necessary, therefore, to notice the effect this has on the total pressure. Experiments have shown that the wind will glide over a smooth surface, such as we have supposed our plane to be, with great freedom. In other words, the skin friction is exceedingly slight. The action of the wind upon the surface is, therefore, in the nature of a normal pressure exerted at every point. For if we suppose the skin friction to be zero, then the pressure at each point due to the wind will be exerted exactly at right angles to the surface at that point. In the case of slightly roughened, fuzzy, surfaces, such as the cloth used in kites, it may not be strictly admissible to wholly neglect skin friction. In this case the air must be regarded as catching upon the roughnesses of the surface and exerting a slight push or force which urges the plane along in the direction in which the streams of air are flowing over its surface. Fig. 29 shows on a larger scale these forces of pressure and friction as they may be conceived to act on a single point, *P*, of the surface. *P′ P* represents the relatively large pressure acting directly at right angles to the surface; *F P* represents the feeble force of friction acting parallel to the plane. From mechanics we learn that the combined effect of these two forces is the same as that of a single force represented by the line, *Q P*, which is the diagonal of a parallelogram formed on the lines *P P′* and *P F*. The total pressure on the whole surface of *A B* is simply the sum of all the elementary pressures like *Q P*. If we may neglect skin friction the pressure of the wind acts at right angles to the surface. If the skin friction is great enough to require consideration, then we must regard the wind pressure as acting at a less angle than 90° to the surface. It may be added here that the wind pressure experienced by a plane surface is due to the diminution of the pressure of the air on the back, or lee side, of the plate as well as to the direct impact of the wind on the forward side. For our present purposes we need not push the analysis so far as to separate these effects but will combine them into a resultant pressure on the front face of the plate.

In Fig. 28 the pressure of the wind at numerous points of

the surface is represented by several small arrows. These are made longer toward the forward edge, in order to indicate a fact, brought out by experiments, namely, that the pressures are more intense over the forward portions of an inclined plate. This is readily understood when we notice that the front edge of the plate receives the full force of the wind which, after having its direction of motion completely changed and made parallel with the surface, glides easily over the after portion of the plate without exerting much pressure. In dealing with pressures of this character we generally desire to consider the total pressure over the whole surface. Such a pressure will be called the *total normal pressure*, or simply *normal pressure*. By way of excuse for what may seem to be a misuse of the word normal in this connection, we may add that although we have already learned that when we include the effects of skin friction the wind pressure can not be strictly normal, that is, at right angles to the inclined surface; yet the friction effect is generally so small that we may for the present include it in the total pressure and still designate the combined effects by the convenient term, normal pressure, without serious inconsistency.

Center of pressure.—It is not enough to know that the total normal pressure on a plane is practically at right angles to the surface; we must also know the magnitude of the force and the point at which it acts. The point of application of the pressure is called the *center of pressure*, that is, the point at which, if all the forces be concentrated, their action produces the same effect as when the forces are distributed and act at every point of the surface. If the intensity of the pressure were the same at all points of the plate, then the center of pressure would be at the center of the surface. It was shown above, however, that with inclined surfaces the forces are most intense near the forward edges, therefore the center of pressure can not be at the center of the surface in such cases.

Many experiments have been made to determine both the magnitude and the point of application of the normal pressure on inclined surfaces of various kinds and for different wind velocities. Exact experiments are difficult to make, however, and the results obtained from various sources are more or less discordant with each other. In regard to the position of the center of pressure it is plain that if the forces are most intense toward the forward edge of the plate, as indicated in Fig. 28, then the center of pressure will be more or less forward of the middle point of the line, *A B*. (We have supposed the form of the plate represented by the line, *A B*, to be rectangular, with the front and after edges presented at right angles to the wind current.) Both the form of the plate and the manner in which it is presented to the wind will have much to do with the location of the center of pressure. Without, therefore, attempting to indicate correctly the location of the center of pressure on the supposed rectangular plate, we may

represent the total normal pressure of the wind on the plate by some such line as *N O*. The angle, *A O N*, will be a trifle less than 90°, if we include the effects of skin friction. The center of pressure will be on the middle line between the right and left edges of the plate. It can not be otherwise, for there is no reason why the pressure of a uniform wind should be permanently unequal on the right and left halves of the plate.

Edge pressures.—The pressure on the forward edge of the plate may be represented by the line, *E P*, in the same way that *N O* has been found to represent the pressure on the under surface, *A B*. To ascertain clearly the total effect of the wind on the whole plate we must combine the forces, *N O* and *E P*. This is effected, according to the principles of mechanics, by prolonging the direction lines of the forces until they intersect and then constructing the parallelogram, *P′ O′ Q N′*. *N′ O′* is made equal to *N O*, and *P′ O′* is equal to *E P*. The diagonal line, *Q O′*, now represents the total effect of all the wind forces acting upon the plate, that is, the wind will tend to push the plate in the direction *O′ Q*, with a force which is represented by the length of the line, *O′ Q*. To hold the plate in equilibrium against the action of the wind it should be sufficient to introduce another force equal to *O′ Q* and opposed thereto, as the force *O′ Q′*, for example.

Fig. 30 represents the action of the wind on the edge of a piece of cloth thickened by the cord in the hem to strengthen the material. The pressure of the wind on the rounded edge will tend to push the edge in the direction *A P*. The combination of this force, with the normal pressure represented by *N O* (only a part of the surface is shown) may be effected by means of the parallelogram of forces *O′ N′ Q P′*. Here, again, the line *O′ Q* represents in magnitude and direction, the total effect of the wind on the surface in question.

In Fig. 30 the normal and the edge pressures are combined at the point *O′*, obtained by the intersection of the lines *N O* and *E P* prolonged. This method is adopted in order to simplify the diagram. We are not to infer that the resultant pressure necessarily acts through the point *O′*. The edge pressure, *E P* exists primarily as a tension in the cord in the hem of the cloth, and as such is communicated to the sticks of the kite. The precise manner of combining the forces in order to locate correctly the point of action, *O′*, of the resultant will require special attention according to the conditions of a particular case, and need not be now considered.

Resultant pressure.—We have already designated the pressure represented by the line *N O* as the total normal pressure. We will now adopt the expression *total resultant pressure*, or simply *resultant pressure*, as the name of the combined effect represented by the lines *O′ Q* in Figs. 28 and 30.

The important point it is designed to bring out in the foregoing treatment of the several pressures upon a plate is to show: (1) that the general pressure over smooth and ex-

tended plane surfaces may be regarded as practically normal to the surface, and (2) that the total resultant pressure on all surfaces (including the edges, sticks, struts, and other members, necessarily parts of the kite structure) is always inclined more or less away from a normal, as indicated by the lines $O' Q$, in the figures.

Thus far we have virtually supposed the plate to be perfectly flat, but kite surfaces, especially when made of paper or cloth, will rarely or never be quite flat, and the effects of curvature must, therefore, also receive our consideration.

Pressure on thin, curved surfaces.—The kind of curved surface commonly met with in kite work is simply the arched or bellied-out surface which results from the pressure of the wind on the more or less loosely-fitted cloth or paper coverings. This looseness is oftentimes intentional, for the reason that experiments show that the total pressure on inclined arched surfaces is greater than on the same extent of flat surface. In Fig. 31, let A B represent a section of an arched surface, such as might exist in a kite. The curved line, A B, may be regarded as the path followed by a particle of air as it flows across the surface from the front to the rear edge. Here, again, so little is certainly known of the exact nature of the pressure of wind on such a surface that we cannot indicate its character correctly nor locate definitely the position of the center of pressure. In the case of a plane surface we found that the total pressure acted sensibly normal to the surface. In the case of arched surfaces we do not know certainly in just what direction the total pressure acts. Lilienthal, who has done so much to advance the art of flight with wings, has made a great many experiments from which he has deduced both the magnitude and direction of the pressure on arched surfaces.[1] His methods of experiment, however, and the results, especially in respect to the direction of the force, are affected by an error pointed out by A. v. Obermayer.[2] While it will scarcely be possible in a given case to predict what direction or at what point the total pressure is acting, yet we may state approximately that the center of pressure, generally, is forward of the middle of the arch, and the direction of action is at an angle of more than 90° to the chord of the arc. The line, N O, may be regarded as indicating the resultant normal pressure. The angle, A C N will generally be greater than a right angle. As in dealing with pressures on plane surfaces we may still consistently designate the total pressure on arched surfaces as the normal pressure, for the reason that it may be conceived to be the sum total of the forces acting normally at every point of the arched surface. The curvature which Lilienthal finds from his experiments to be the most effective

[1] Der Vogelflug als Grundlage der Fliegekunst. Otto Lilienthal. Berlin. 1889.

[2] Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften. Vienna. October, 1895.

is that which makes the height of the arch about one-twelfth of the chord.

The foregoing analysis of the wind pressures on surfaces has been carried out in considerable detail because these matters are of fundamental importance in arriving at a clear understanding of the action of the kite. One can not ignore them and at the same time proceed intelligently to improve and perfect kites.

Effect of waviness, or fluttering.—It often happens, especially with some forms of kites, that the cloth fails to remain taut and smooth, but forms a series of waves flowing in the direction in which the wind moves over the surface. A section across a surface of this character will have some such appearance as shown in Fig. 32. The action is oftentimes very pronounced, and the kite emits a comparatively loud sound, due to the rapid fluttering of the cloth. The effect of this is a matter of serious consequence. The wind presses strongly upon the windward sides of the waves, and thereby tends to push the surface along in the direction $A\ B$. Supposing the surface free of waves, the resultant pressure might be represented by such a line as $O\ Q$. If, however, the wavy condition prevails, the resultant pressure will take such a direction as $O\ Q'$.

Whirls, or eddy effects.—There is another respect in which the action of the wind on the kite may be objectionable in character, that is, may tend to depress the kite or drag it onward with the wind. In the absence of a better name this may be called the whirl or eddy effect. In some forms of kites a greater or less portion of the whole current of air affected by the presence of the kite is broken up into numerous whirls and eddies. These may be formed when the air flowing against the kite is suddenly stopped, or when its movement is abruptly changed and diverted to a new direction. Angles and changes in the continuity of the surfaces such as formed by the presence of the cross stick in the Malay kite, for example, and other causes that prevent the air from flowing easily and by smooth changes of motion over and past the kite, will give rise to eddies. Whirls of marked character exist over the leeward surfaces of the kite. Strong eddies may thus be set up at numerous points adjacent to the body or surfaces of the kite. It is possible, and indeed quite probable, that some of these may remain nearly stationary in certain favorable spots. Such eddies or whirls, in a certain sense, may have much the same effect as obstructions to the flow of the air. Quite as much of an obstruction may be thus formed as if an excrescence of rigid material were placed on the kite at one of the points in question. In cellular kites generally the cells are virtually short tubes through which large streams of air must flow. Pronounced eddy formations within these tubes have much the same effect as real obstructions by which the flow of the air is as it were choked up.

We can not attempt here to analyze in detail the action of

these eddies. The illustrations employed above to aid the mind in forming a conception of some of their effects are known to be faulty and imperfect and open to the criticisms of the exact physicist. Nevertheless, we perceive, by the aid of the comprehensive principle of the conservation of energy, that the power required to form these eddies and maintain the air within them in rapid motion must be derived by reaction from the kite and its string. The necessary reaction can be derived from the kite only when its angular elevation is depressed in consequence.

It, therefore, results that when eddy effects are present with a given form of kite, any modification that will eliminate or lessen the eddies will enable the same kite to obtain a higher elevation, other things remaining the same.

We have already said that the equilibrium of any form of kite depends upon the action of three forces, one of which is the wind pressure. In the foregoing discussion we have aimed to show the complex nature of the force that we call the wind pressure. We will next endeavor to show the conditions which exist when equilibrium is established between the forces in question. It is well known by experience that a condition of equilibrium is possible between the forces which act on a well built Malay kite, therefore we will first select this form of kite as the subject of our analysis. As seen from the front, the kite appears as shown in Fig. 33. The surface is far from being flat. The line *A B* is straight, but *C D* is bowed forward, as indicated by the curved dotted line, *C D*, Fig. 34. Owing to its looseness the cloth is bellied backward by the wind pressure so that in a cross section on a line such as *c d* the kite appears as shown in Fig. 34. Similarly a section on a line such as *a b* appears as shown in Fig. 35.

The kite is held in restraint by means of the bridle which is attached only to the midrib of the kite. In certain respects, therefore, we may regard the midrib as a fixed axis about which the kite may tilt laterally more or less. We will first consider the equilibrium of the forces on the lateral halves of the kite.

Lateral stability.—In the case of loosely fitted coverings, the arching back of the surfaces in the manner indicated in the drawing is very pronounced, and tends to increase the stability of the kite against tilting edgewise to the wind.

The two halves of the kite either side of the midrib, *A B*, must be made very carefully, equal and similar in all respects. When so made, the pressures, acting as indicated in Fig. 34, will just balance each other in a uniform wind, and the kite will then poise on what we may call an even keel. When, however, from variations of the wind, the pressure on one side becomes greater than that on the other the kite is tilted over to some extent. The wing which momentarily received the greater pressure is moved laterally into a position of less inclination to the wind, and the intensity of the pressure is thereby diminished; whereas, the opposite wing being placed

by the tilting in a position of greater inclination to the wind receives a corresponding increase of pressure and a balance between the opposing forces on the two wings is still preserved. If the covering of the kite is taut, so as to remain flat, the cross-section on *c d* will appear more nearly as shown in Fig. 36. A kite with such a surface is also able to preserve a condition of equilibrium between the pressures on the two wings, for the surfaces by tilting more or less assume different degrees of inclination to the wind, and within reasonable limits a condition in which the forces are balanced is possible at all times. The bending backward of the lateral wing surfaces so as to form a dihedral angle, as shown in Fig. 36, lessens slightly the angle of inclination of the surfaces to the wind. The lifting effect in such a case is, therefore, less than with the same surface not so inclined, for it is plain that if the two wings were bent backward to such an extent as to meet each other, all the lifting effect would be gone. The slight loss in lifting power which occurs for the reason here given is, as it were, the price we must pay for the stability imparted to kites of this type. The amount of bending backward ought to be no greater than is required to contribute a sufficient safe-working stability.

If, however, the cross stick of the kite is not bowed or inclined backward in any manner and the covering is taut, the whole surface of the kite will be sensibly flat. Made in this way, the kite will be found to have lost all its lateral stability. Tilting sidewise does not, as formerly, restore the balance of forces, for, with a flat surface, a change of inclination affects the pressure on the whole surface in the same way, and there is no tendency for the tilting to produce a balance between unequal forces on the two halves of the plane. A perfectly flat kite of a single surface can not, therefore, be made to fly of itself. Tails will be required and other artifices must be adopted to keep it poised in the wind in a flying attitude. Even approximately flat surfaces, however, rarely or never exist in kites as ordinarily made. The wind pressures bend the sticks and belly out the covering in nearly all cases to such an extent and in such a manner that at least a slight condition of automatic stability is imparted to the kite.

We have explained in the foregoing how the forces on the lateral halves of the Malay kite surface automatically balance each other, even when the wind pressures are not uniformly distributed. We will next consider the equilibrium of the forces in a longitudinal sense, or in the fore and aft dimension of the kite.

Longitudinal stability.—We have already mentioned that the kite is restrained by means of the bridle attached only to the midrib. We need to now consider how the pressures of the wind upon the cloth surfaces are communicated to the members of the structure and finally to the midrib itself. The fibres of the cloth can resist the pressure of the wind only by virtue of tensional strains. Referring again to Fig.

34, the arched surfaces of the cloth there shown are under considerable tension, which, at the midrib, E, is exerted in the directions of the tangents $E\ T$ and $E\ T'$. There are similar tensional forces at C and D, which act upon the cord forming the perimeter of the kite. These strains are communicated in turn to the extremities of the two sticks, thus reaching the midrib directly or by means of the cross stick. The effect of the two forces, $E\ T$ and $E\ T$, is equivalent to a single force, $E\ P$. By a similar treatment of the reactions at the several portions of the kite frame, it will be found that all the forces may be concentrated upon the midrib. Let $A\ B$, Fig. 37, represent a side view of the midrib with the bridle attached. From what has preceded, it will be easily understood that the magnitude and direction of the total resultant pressure of the wind upon the kite may be represented by such a line as $Q\ O$. The center of gravity of the kite may always be found by well-known methods. Let g be the position of the center of gravity, then we may represent the weight of the kite by the line $g\ w$. The combined effect of both gravity and the wind is now found by means of the parallelogram of forces, $O'\ Q'\ R\ G$. The force represented by the line $O'\ R$ is the resultant effect of both the wind and gravity on the kite. The kite can be in equilibrium only when the string pulls in line with the force $O'\ R$ and through the point O'. The string from the bridle must, therefore, take the position and direction shown, viz, $O'\ F\ L$, and the tension on the string must be numerically equal to the force $O'\ R$.

Diagram of forces.—Fig. 37 is a typical diagram of the action of the forces on any kite. Such a diagram, especially that part including the parallelogram, $O'\ Q'\ R\ G$, and the string, $L\ F$, will hereafter be designated as a diagram of forces. We have mentioned before that the force of the wind is the only force that varies independently; that is, the line $O\ Q$ in the diagram requires to be made not only of different lengths, to represent, from moment to moment, the changing intensity of the wind force, but both the direction of the line, in relation to $A\ B$, and the position of the point O, are also constantly changing in correspondence with changes in the direction of the wind in reference to the kite. These changes of direction are partly real changes in the wind, but are also due to changes in the angle of incidence of the kite. The angle a in the diagram may, for present purposes, be regarded as the angle of incidence.

To follow a little further the action of the forces on the kite, let us suppose the wind pressure to increase in intensity without change of direction or point of application. Let the increased pressure be represented by the line $O'\ Q''$. The new resultant of the forces of wind and gravity will be the line $O'\ R'$. The pull of the string acting through the point O' is now no longer able to just oppose and balance the new resultant $O'\ R'$. These two are inclined to each other at a slight angle, instead of being exactly opposite in direction. Re-

sorting again to the well known method of the parallelogram of forces for combining the now unbalanced forces on the kite, we find that there exists a small unbalanced effect, such as indicated by *O′ M*, which urges the kite forward and upward in the wind. (To avoid confusion, the lines of the parallelogram are omitted from the drawing.) The movement which results from the action of the force *O′ M* causes several changes of conditions, thus, the angle of incidence changes, the direction of the string is made steeper; the point of application of the resultant wind pressure shifts and the force also changes in direction. By means of these changes new conditions are established in which complete equilibrium of the forces again results.

We may now see the reason for using the bridle *E F B*. If the string were tied directly to the kite at *F*, for example, the kite could be in equilibrium only when the *resultant* of the wind pressure and gravity passed through that point. Tied to the point *F* the point of intersection of the string with the kite can automatically shift and thus accommodate itself to numerous conditions. Moreover, the tension of the string acting at *F* and the wind pressing at *O* constitute a system of forces that are in stable equilibrium.

This advantage of arranging the string to draw from a point at a distance in front of the kite suggests that it be employed likewise to increase the lateral stability of the kite. For example, if *E F*, Fig. 38, represents the bridle as it is seen in the end view of the kite, the point *F* may be made fixed in reference to the kite by use of two steady lines attached to points on the cross stick, as at *f f*. Such, or an equivalent arrangement, that produces a fixed point in front of the kite from which the string may draw, will be of special advantage in the case of single plane kites whose surfaces are very nearly flat.

For the sake of simplicity it has been assumed in all that precedes concerning the diagram of forces, that the angle of inclination of the total resultant wind force, *Q O*, to the line, *A B*, can not be as great as 90°, which, for flat surfaces, represents an ideal condition of absolutely no edge resistance, skin friction, etc. This, however, may not necessarily be the case with arched surfaces, for we have already had occasion to point out, as shown in Lilienthal's experiments, that the total resultant pressure on certain thin arched surfaces may be inclined *forward* of the normal to the chord of the arch. Nevertheless, when ill effects such as those illustrated in Fig. 39 exist, the slight possible advantage gained by the effects of arched surfaces is more than offset by the defects that have been pointed out. Our assumption that the angle, *Q O B*, is less than 90° for both flat and arched cloth surfaces as ordinarily found, can not, therefore, be much in error. Furthermore, there is positive evidence from the experience of every flyer of the Malay kites that the angle of the total resultant force, *R F′ B*, can not be as great as 90°. For, the angle, *B E F*,

of the bridle is generally made at least 90°, and if $R F' B$ ever becomes as great as 90° it would mean that the lines $F L$ and $E F$ would coincide. A very slight acquaintance with kite behavior will convince one that this does not occur in practice. The direction of the string at $F L$ always falls between the strings $E F$ and $B F$.

Up to the present point we have proceeded to draw the diagram of forces as if the force, $O Q$, were fully known in magnitude, direction, and point of application. In practice this is just what we do not know. It is plain, however, that we may measure both the direction and the pull of the string at $F L$, and also determine its point of intersection with the kite. Furthermore, the weight and the position of the center of gravity of the kite are always determinable. Knowing, therefore, the resultant and one force for any given case, we are able to work the parallelogram of forces backward, as it were, and thus arrive at a complete knowledge of the unknown force, $O Q$.

Conditions that modify the angular elevation of the kite.—The direction of the string, $F L$, that is the inclination of the top end the kite string to the plane of the horrizon, considered in connection with the angle of incidence of the kite, is a fundamental datum in the analysis and comparison of the behavior of kites. When the string, from the ground to the kite is short and sensibly straight it will be noticed that the direction of the string at $F L$ measures the angular elevation of the kite from the reel. Any arrangement or modification which can make this line steeper, other conditions remaining the same, will be an improvement, for it means that the kite will tend to fly that much nearer the zenith. Bridling the kite so that the angle of incidence a is smaller will, in general, cause it to fly more nearly overhead, but we do not wish to consider this case now for the reason that lessening the angle of incidence lessens the pull of the kite at the same time. It is designed to consider here only those modifications that will increase the steepness of the line $F L$ without any change of the angle of incidence. We will reserve, for future consideration, the question as to what angle of incidence is best.

Let us observe the effects of the weight of the kite itself. In the parallelogram of forces, Fig. 37, the line $O' G$ represents the total weight of the kite. If the weight of the kite can be diminished then the line $O' G$ will be shorter in relation to $O' Q'$, and a new resultant, $O' r$, will be formed having a steeper angle than the resultant $O' R$. As the kite string in the new condition must come into line with $O' r$ we see that lessening the weight will cause the kite, other things remaining the same, to stand at a higher angular elevation. It will be noticed, also, that the resultant $O' r$ is longer than $O' R$; that is, the pull of the kite is greater.

There is another respect in which something may be done to increase the angular elevation of the kite. The line $O Q$

representing the total resultant wind pressure on the kite is not at right angles to *A B*. The angle *Q O B* is less than 90°. As has already been explained the influence which deflects the line away from the normal is the pressure of the wind on the edge surfaces of the kite. It may appear that a kite of the Malay type presents a very small extent of edge surfaces upon which the wind can act. However, such is often only seemingly the case. By referring to Fig. 39, which shows a sectional view of the kite on such a line as *a b*, Fig. 33, we notice that owing to the arching upward of the cloth in front of the cross stick *C D*, the greater part of the surface *A C D*, Fig. 33, is presented to the wind at a much greater angle of incidence than the rest of the surface. In a certain sense this triangular front of the Malay kite as it narrows out to the points *C* and *D* is little else than an edge surface, and the wind pressure thereon is of the same harmful character as upon real edge surfaces. The normal pressure on this surface takes such a direction as *O N*, Fig. 39, and when this force is combined with the other pressures that act more nearly at right angles to the kite surfaces, the total resultant is inclined away from the normal more than would be the case in the absence of these harmful pressures. Returning now to Fig. 37 we notice that any influence which causes the line *Q O* to incline backward and away from the normal to the line *A B* will have the effect of giving a smaller angular elevation to the line *F L*, when equilibrium of the forces exists.

The above study of the diagram of forces has thus far led to two noteworthy conclusions, namely: (1) that changes in the weight of the kite have a direct effect on the pull of the kite and cause the angle of intersection of the string with the kite surfaces to change, thereby changing the angular elevation of the kite; (2) that the blowing backward and upward of the loose cloth in front of the cross stick *C D* in kites of the Malay type has a very prejudicial effect upon the angular elevation of the kite. We may mention with these the following conditions which also tend to lessen the angular elevation of the kite, namely: (3) all pressures upon the edges of the kite; (4) the surfaces of the kite may flutter and take on a wavy character under the action of the wind. Attention was called to this ill-effect in a previous paragraph; (5) eddy effects.

Considerable attention has been given to the effects of edge pressure, whirls, waviness, etc., all of which cause the total resultant wind pressures on surfaces to take an inclined, rather than a normal, direction to the surface. In developing the kite so as to reach great elevations, any influence which tends to deflect the resultant wind pressure away from the normal to the kite surfaces tends to depress the kite away from the zenith by the same angular amount, and one most important point, therefore, in which to improve the kite is to diminish and eliminate, as far as possible, the edge pressures and all similar effects.

It is plain, therefore, as a result of the foregoing development of the ill-effects due to certain features of kite construction, that the expert designer must aim not only to make his kites as light as possible, but all waviness and fluttering must be suppressed, and all those influences which tend to deflect the direction of the total resultant pressure away from the normal be eliminated and diminished as far as possible.

We are now brought to the statement of a very important principle, the significance of which will more fully appear as the study of the action of the forces upon the kite is carried further. The principle has to do solely with the *direction*, relative to the kite, in which the wind pressure acts upon it. The *magnitude* of this force is a matter for separate consideration. The principle may be stated as follows: *The condition of ideal efficiency (that is, an efficiency of* 100 *per cent), in the action of wind forces upon a thin plane surface, obtains when the total resultant pressure is exactly normal to the surface.* The line $Q\,O'$, Fig. 28, will, in the ideal case, form a right angle with $C\,D$ and be in the plane of the paper. With material plane surfaces the angle $Q\ O'\ P'$ will generally be less, it can not be equal to or greater than a right angle. We have seen that with an arched surface the resultant may make an angle greater than 90° with the chord of the arc, but we are unable for the present to extend the above principle to the case of arched surfaces, as thus far no sufficiently exact knowledge of the direction of the resultant pressure exists to justify a statement of its limiting direction in the ideal case. In the development of the kite for the purpose of reaching very lofty elevations, the action of the wind upon it should exhibit the highest possible efficiency as the word is defined in the principle enunciated above. All those actions or effects which tend to incline the resultant away from the normal will cause the kite to be correspondingly depressed in angular elevation. Since for meteorological purposes, other things remaining the same, we aim to secure the maximum possible angular elevation for the kite, those effects which tend to depress the kite in angular elevation are of a harmful character and it will be convenient, hereafter, to employ the word harmful in this sense.

It will not be appropriate in the present article to discuss the diagrams of forces for different cases of wind force and direction, nor to develop the best arrangement of bridles, etc. Many experimental difficulties are encountered in seeking exact numerical solutions for ordinary practical cases, and many observations are required. The writer having indicated, in a general way, how the action of the forces affecting the kite may be studied, hopes that experts at work on the problem may test these ideas, pointing out errors and defects that doubtless exist, but especially that they may set about securing the observational and numerical data which are so much needed in order to convert the kite, hitherto almost without exception the toy of boys and men, into the highly

efficient and useful piece of scientific apparatus which it seems destined to become.

FORMS AND CONSTRUCTION OF THE WEATHER BUREAU KITES.

The modification of the Hargrave kite, devised by Mr. Potter, and which we have called the diamond-cell kite, was extensively tested in our first experiments. The details of construction of this kite have been minutely given in the MONTHLY WEATHER REVIEW for November, 1895, and their repetition here will not be necessary. The kite is shown in Fig. 40, from which the construction will be understood. Numerous minor variations were made in the main proportions, and in the dimensions of the sticks, etc. The main object in view at that time was to reduce the weight of the kite as far as possible without impairing the strength to such an extent that it would break when severely strained in the wind. This was effected by tapering off the sticks and otherwise shaping them so that the greatest amount of material was concentrated at the points of the greatest strains. This form of kite is exceedingly simple of construction and possesses the advantage of being collapsible for convenience of storage or transportation.

One defect that may be pointed out in the diamond-cell kite consists in the presence of the comparatively sharp angles between the cloth surfaces where they meet at the side edges of the kite. The upper surfaces are greatly sheltered by the lower surfaces near these side edges, and we can readily perceive that eddies, whose harmful effects were pointed out in a preceding paragraph, must be present to a serious extent. The writer devised and tested during December, 1895, two forms of multiplane kites, in which it was sought to avoid the objectionable effects of the sharp angles referred to above and still secure lightness of construction. Fig. 41 shows the first form tried. The result was a failure, so far as flying successfully was concerned. The two very small webs of cloth, *a a*, were the only vertical surfaces introduced, and the trial proved that the kite lacked those steady, stable qualities so generally found in kites of the cellular type. It was concluded that good results could be obtained by connecting the outer ends of the horizontal sustaining surfaces with cloth, so as to form a greater extent of side surfaces adapted to steady the motions of the kite.

The second form of kite carried out this idea. It is shown in Fig. 42. The only kite made of this kind was unsatisfactory because the frame work proved to be too light. Its flying qualities seemed to be as good as those of most of the kites tested at that time. The side planes are so steeply inclined as not to form the sharp angles found in the diamond kite.

Further experiments with these forms were resumed on different and better lines after the studies and experiments relating to the strength of the wire, the manner of splicing, measuring, reeling it, etc., were made.

While this work was in progress during the early part of December, 1895, a great variety of forms of kites were considered by the writer, even though time was not then available to make up and test them. The more important of these forms are shown in Figs. 43 to 46. Bearing in mind the conditions which ought to be satisfied by a good kite (p. 41), a brief mention of the points of advantage in the several designs will be sufficient.

Fig. 43 represents a Malay kite with an upper or superior sustaining surface, *a*. It will also be noticed that the bowed cross-stick, *C D*, is in front of the cloth. The object of this is to eliminate the harmful effects pointed out in connection with Fig. 39. The presence of the superior sustaining surface will cause the center of pressure to fall back of the midrib and thus tend to increase the lateral stability, which may be further improved by use of a bridle arranged according to the principle to which attention was called in connection with Fig. 38. In order to steady the kite a vertical web of cloth, or dorsal fin may be required. Both these modifications are shown in Fig. 44.

Fig. 45 indicates the application of a relatively weak propelling apparatus to the line beneath the kite. Such a device, if not too heavy in proportion to the lift of the kite and the thrust of the propeller, will, as shown, cause an angle to be formed in the string near the kite, so that the portion below the propeller is much more nearly vertical than the portion next the kite. The advantages of this will be more fully brought out when we treat later of the properties of the catenary or the curve formed by the kite wire or string. The motor is supposed to be operated by energy stored within, or by electricity, or possibly the necessary energy may be derived directly from the variations in the wind itself. It is well known that the wind constantly varies in force. Imagine the propelling arrangement to be driven by a steel spring, it is plain that with the aid of suitable mechanical devices every time the force of the wind increased the greater tension on the wire could be made to wind up the spring more or less. Or, the variations in the wind force might be made to flap wings in some useful manner. If the variations in the wind force proved to be inadequate the wire at the reel might be alternately pulled and slackened so as to produce considerable variations of tension. These ideas, it is believed, possesses some novelty and possible merit.

Fig. 46 shows the original idea from which the kite illustrated in Fig. 42 was evolved.

Mr. H. Chadwick Hunter of Washington, D. C., who interested himself in the kite work of the Weather Bureau, and who flew kites for his own amusement and outdoor exercise, introduced a noteworthy modification of the diamond-cell kite. This was in December, 1895. A Malay kite was cut in half lengthwise, and the triangular segments thus formed attached to the sides of a diamond kite, forming the winged

kite shown in Fig. 47. Considerable additional sustaining surface is thus gained, with but a slight increase of weight. Several kites of this type were employed in the Weather Bureau work. In some the wing surfaces were made quite large. The results, however, were not so satisfactory. Seemingly, the best proportions are obtained when the greatest width of the triangular wing is not more than one-half the longitudinal dimensions of the kite. A greater width than this will answer well in light winds, but stronger winds are likely to disturb the symmetry of the kite as a result of unequal stretching of the material. Kites of this form took the highest angular elevation of any tested at that time, but experience showed that they could not be fully depended upon to stand as great extremes of wind force as the kite without wings. I think there is much merit in this kite, and it seems probable that by using a heavier and firmer grade of cloth for the wing surfaces, the effects of uneven stretching of the cloth will be less serious or of no consequence. Whether the corresponding increase of weight would detract seriously from the advantage gained by the addition of the wings can only be certainly told by experiments.

It is worth noticing that the amount of sustaining surface in a given kite is a fixed and invariable quantity, notwithstanding that the kite is called upon, or at least we wish it to withstand great extremes of wind force. Up to the present time no attempt appears to have been made to provide arrangements, automatic or otherwise, for increasing or shortening sail. Present practice in kite flying is like sending a yacht to sea with every sail set and without means for either reefing or furling them. The air ship, it is true, does not carry its sailors aboard, but it is not impossible that it may in the future. In the mean time inventive genius needs to provide some means by which the sustaining surfaces of a kite may be easily varied without proportionate variations of weight. One kite may thus be adapted to great extremes of wind force.

In the literature of kites we find the use of flexible surfaces strongly recommended, because, it is stated, the bending of the surfaces under gusts of wind eases off the severity of the strain and is otherwise attended with good effect. We have in this a means of automatically adjusting the expanse of sail to the force of the wind. The idea is good enough, in its way, but when we examine into the degree of flexibility provided and compute the diminution in pressure resulting from the maximum possible flexure, it will be found that the provisions ordinarily made will prove entirely inadequate and that the great advantages claimed are largely imaginary. The force of the wind at 30 miles per hour is fully nine times as great as at 10 miles per hour. The supposition that the flexure of a wing surface of a few degrees can contribute in any important degree to compensate for nine-fold variations in pressure, is plainly untenable. We shall have occasion later to discuss this point to some further extent.

The winged kite, described above, may easily be constructed in such a way that the wings may be removed or furled, and the amount of sustaining surface correspondingly diminished when strong winds prevail. This is perhaps a first step in the direction of providing a variable expanse of sustaining surfaces.

Mr. Hunter also devised and constructed the kite shown in Fig. 48. This was very successfully flown early in February, 1896. Other forms of kites proved to be superior, however, and more desirable in several respects.

It is important to notice that a kite almost precisely similar to the winged cylinder kite of Mr. Hunter was devised by Mr. W. H. Hammon, Forecast Official, in charge of the Weather Bureau office at San Francisco, Cal. Accounts of the first trial of this kite were published in the San Francisco Chronicle of April 2, 1896.

Fig. 49 is a drawing made from a photograph of this kite. Mr. Hammon dispensed with the ordinary bridle as a means of adjusting the string to the kite and adopted a novel bowsprit arrangement. His device is described in his own words as follows:

> Instead of attaching the string to the kite by a bellyband, I use a stick, the end of which is attached to the backbone of the kite about two-thirds of the distance back from the front edge of the first cell and then passed diagonally through the cell and out at the bottom of the front edge, where it is also fastened and extends about 16 inches downward in this diagonal direction. The string is then attached to this lower end.

Speaking of securing automatic adjustability to winds of different force, he says this is also gained:

> By attaching the bowsprit to the upper side of the cell only and then passing it through a rubber hose attached to the front edge of the lower side of the cell instead of to the cell itself. The string is then fastened to the hose instead of to the bowsprit. The point intended to be gained is that the cell will spread with a high wind, thus narrowing the surface normal to the wind and diminishing the strain upon the string, at the same time the bowsprit will be drawn further back in the hose, thus shortening the distance it extends below the lower edge of the kite, which causes the kite to hang more nearly parallel to the wind and thus diminishes the strains upon the string.

A kite of this form has not thus far been tested at Washington.

Attention has already been called to the tendency of the cloth covering of kites to form waves and to emit a comparatively loud sound caused by the fluttering. The manner in which energy may be wasted in this action has also been shown. The full significance of this action did not force itself upon me, at first, and many experiments were made with kites of various forms, the cloth of which, scarcely without exception, fluttered more or less at all times.

When the actual work of constructing improved forms of kites was resumed after the special investigations upon the best arrangement of kite line, reel, etc., were completed, the writer had become fully awakened to the importance and harmful effects of waviness, eddies, edge pressures, etc. After

careful thought in the light of this knowledge, he was fully convinced that the simple rectangular cell of the regular Hargrave kite is a most excellent form of cross section of the cell. The sustaining surfaces are disposed in the position of maximum effectiveness, as are also the vertical side surfaces, whose special function is to steady the motions of the kite and contribute to the lateral stability thereof. The causes which can produce eddies are present in less degree than in many of the forms already described. The plan of construction practiced by Hargrave and followed by Mr. Potter does not, however, prevent fluttering of the cloth. From these considerations, however, I am led to the belief that the simple rectangular cell is already the best form we have as the basis of cellular and multiplane kites.

The problem was, therefore, how to improve this kite. To solve this problem the writer sought (1) to lessen the weight of the kite without loss of strength; (2) to reduce harmful edge resistances; (3) to suppress waviness and fluttering; (4) to lessen and eliminate eddy effects, and, finally, in order to increase the pull of the kite, other things remaining the same, (5) to arch the surfaces of the cloth.

The plan practiced by Hargrave of constructing the frame of the rectangular cells is shown in Fig. 50, so far as it can be made out from the general illustrations published by him in American Engineer, April, 1895. The details of the joints in Fig. 50 are due to Mr. Potter, and while the suggested construction there indicated may be helpful to beginners, the point has no important bearing on the general plan of the frame. The important dimensions of a kite made according to this plan are indicated on the drawing. The sustaining surface of the kite is 24 square feet. The dimensions of the sticks (straight-grained white pine), where important and not shown on the drawing, are as follows:[1] All diagonal struts are $\frac{1}{2}$ inch square, shaved round and notched and cleated on the ends. The struts are firmly lashed together at points of crossing. All longitudinal sticks (six in number) are $\frac{1}{4}$ by $\frac{5}{8}$ inch, edges rounded. The four lateral longitudinal sticks are made narrow between cells. These sticks need not be made continuous. They were not so made by Hargrave. By making them continuous and stringing them with a complete system of diagonal ties made of fine, spring, phosphor-bronze wire, the frame of the kite is better able to withstand twisting and distortion. Made in this way the kite will prove to be an excellent flyer, and with winds of 12 miles per hour and over will be capable of reaching considerable elevations.

Improved construction.—A modified construction of this form of cell is shown in Fig. 51. This, so far as known to the writer, has not been employed or described before. Sufficient details are therefore given to enable others to use it, if desired.

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[1] To avoid repetition here, the reader is referred to the MONTHLY WEATHER REVIEW for November, 1895, for minute details concerning the construction and joining of the framework.

Rectangular frames.—Slender frames, square dovetailed at the corners, as shown in Fig. 52, constitute the basis of the cells. The frames are made remarkably strong and rigid against forces acting in their own plane by means of the diagonal wire ties and the strut through the middle. The sticks for kites of from 24 to 40 square feet of sustaining surface are of $\frac{1}{4}$-inch white pine, or spruce, $\frac{5}{8}$ inch wide, slightly more or less in proportion to the surface. All wire ties are of the best phosphor-bronze spring wire, 0.028 of an inch in diameter. To insert the wires so as to insure accuracy in the form of the frames, strips of wood are nailed to the top of the workbench so as to form a true rectangle, within which the slender frame will snugly fit. The end of a wire is passed through inclined holes at *A*. A small fragment of sheet tin is placed under the wire to prevent it from cutting its way into the wood when strained. One end of the wire is carried around the joint *D* and twisted in the manner shown. If not already done, the frame must now be placed within the rectangular form on the workbench. While held in perfect shape therein the remaining end of the wire is passed around the joint at *C* and secured by twisting while under considerable tension. The strut *A B* is generally only temporary. Any small stick answers the purpose, and it need not be secured within the frame in any way except as it is held by friction. The longitudinal truss on midrib of the completed kite generally takes the place and serves the purpose of the strut *A B*. The frame is completed when the wire *E B F* is inserted and fastened.

To secure the proper tension on the wires requires a little experience. Too much tension may easily be obtained, although if the knack of twisting both the wires equally is not possessed the joints may slip and the wire become too slack. With the right degree of tension the frames warp more or less out of true when taken singly. This is corrected when the frames are assembled.

In describing the best manner of splicing wire by twisting it was pointed out that both wires must be twisted around a common axis. The wire ties in the frame just described must be twisted in the same way. It takes but a moment to solder the twisted joints, and their strength is very greatly increased. The wire is also soldered to the pieces of tin at *A*, *B*. The wires at crossings are sometimes wrapped with finer wire and soldered; often, however, they are simply tied with fine strong waxed twine or thread.

The next member of the frame work is the piece employed to join the frames with each other at the corners. Fig. 53 shows the form of the stick and the tin angle pieces at the ends. The stick, originally $\frac{1}{2}$ inch square, is shaved down tapering and parallel to the diagonal to about $\frac{1}{8}$ inch at the ends. The tin angle pieces are secured to the ends of the stick by lashing with No. 22 gilling thread thoroughly waxed.

The cell.—The manner of connecting the frames with each

other is shown in Fig. 54. Two connected frames constitute the cell, minus the covering. This is simply a long band of cambric, generally ½ yard wide. After the strip of cloth has been torn to width and hemmed, the length is ascertained by stretching the edge around one of the frames, marking off, with pencil, where the stitching is to come. The opposite edge of the band is stretched around the frame in a similar manner and marked. The ends of the cloth are laid out smooth and pencil lines drawn across from the marks at the edges. These lines are overlapped and matched exactly. The cloth is then stitched on the mark and the seam finished as suits the taste of the operator. This method gives a cloth covering that fits perfectly. The tightness with which the cloth fits may be varied to suit circumstances. The cloth need not in any case be very tight.

The complete frame of the cell may be put together and the cloth slipped over afterwards. This requires some care to avoid pulling the cloth awry. I prefer to set up two of the frames on edge and connect them at the angles by means of the connectors shown in Fig. 53, three of which are simply laid in place between the frames with the band of cloth loosely on the outside. When the fourth is put in place the cloth comes under tension and all the parts hold together with some security. The corners may then be lashed together, as shown in Fig. 54. The edges of the cloth are secured to the cell by tacking it to the frames at intervals of several inches. I prefer, however, to secure it by sewing through the hem of the cloth and around the sticks of the frames. Stitches between one and two inches apart are sufficient. Fine bookbinders twine is generally employed for this purpose. Fully two square feet of sustaining surface is gained in a kite of thirty-two square feet, by this method of sewing, as it is not necessary to make the cloth overlap the frames.

Longitudinal truss.—Two cells joined by some sort of longitudinal truss make the complete kite. Several methods of trussing the cells together have been tried, but thus far, I think the strongest, most rigid and at the same time sufficiently light truss has not been developed. In the first kite made according to the new construction, the cells were connected at their four corners by a different plan than described above. Four long connecting pieces extending the full length of the kite were employed, and in another case two strong trusses similar to one shown in Fig. 55 were placed, one at either side of the kite. Either of the above plans of connecting the cells forms a very rigid and strong kite frame when reinforced with diagonal ties of wire. The principal objection to the arrangement of trusses just described is the fact that no good place results at which the bridle can be attached. Either an additional piece or supplementary truss must be placed in the central or median plane of the kite to which a simple bridle may be attached, or, in the absence of such a

piece, a more complicated bridle must be rigged to draw from the lateral lower edges or corners of the cells. The first plan requires the addition of weight that ought not be necessary. The bridle of the second plan when under tension produces heavy compressive strains upon the frames of the cells, increasing the load these frames already carry as a result of the direct wind pressure upon the cloth. Neither plan is therefore quite satisfactory. The manner of joining the cells, illuslustrated in Fig. 51, was subsequently adopted and found more satisfactory. The truss itself is shown in Fig. 55.

The first kite made with a truss of this form is shown in Fig. 56. The slender, diagonal side braces *a a* and *b b*, Fig. 51, had not, at that time been introduced. Without them the kite lacks rigidity against forces acting at right angles to the plane of the truss. No difficulty on this account ever occurred with the kite shown in Fig. 56, which has seen a great deal of service, but the diagonal side braces are considered an improvement in most cases. Furthermore, in flying these kites in tandem mishaps caused by the main wire getting caught *between* the cells of the kite are prevented when the cells are connected with each other at their lateral edges. Very slender connectors are adequate both to stiffen the frame and to keep the wire from between the cells.

Advantages of construction.—The distinctive feature in the above described construction of the cells lies in the fact that the cloth is bound with wood at all edges. Being thereby made perfectly firm and rigid, it is found the cloth exhibits no tendency whatever to flutter or break up into waves. The kite flies in perfect silence, save a slight whistling of the wind over the wire ties. It is believed there is another important advantage in this construction, namely: a slender vertical strut, at *A B*, $\frac{1}{4}$ inch thick, is the only obstruction to the free flow of the air through the interior of the cell, except the fine, diagonal tie wires. Referring to the Hargrave construction, shown in Fig. 50, it may seem, at first thought, that the slender diagonal struts employed can have but very little harmful influence. When we remember, however, the effects of eddies and observe that the struts themselves and especially the relatively bulky knobs at the ends, where they thrust against the longitudinal members of the frame inside the cell, as also where they cross, are all fruitful causes of eddies, we are forced to the conviction that their elimination can not fail to prove highly beneficial. In the improved construction described, the minimum obstruction is offered to the easy flow of the air over all the surfaces and through the cells of the kite. In the old construction the edges of the cloth are thin and perhaps form a sharper cutting edge than the $\frac{1}{4}$-inch rounded wooden frames with which the cloth is edged in the improved construction. I am inclined to think, however, that the thin edge of the cloth has only seemingly the advantage here. The contrast and comparison must be drawn between the thin, pliable, possibly loose and fluttering edge

of cloth and the smooth, rigid, slightly thicker wooden edge. I am strongly convinced that the actual edge pressure upon the wood with even the bluntly rounded edges I have employed is but a trifle if any greater than upon the thin edges of cloth, as ordinarily found, and which is loosened up considerably in a very few minutes when exposed to the wind, even when originally made very taut.

The superiority of the new construction as brought out by the above analytical considerations is abunnantly sustained by the results of exact observations and measurements. These will be presented in a later section of this article.

The principal objection I entertain to the construction which has been described is the weight[1] of the frame which, thus far, has been found to be some 20 per cent heavier than frames of similar size of the Potter-Hargrave construction. Even though handicapped by this greater weight, the performance of the kite, owing to the advantages already pointed out, surpasses in excellence that of any kite yet tested. On account of weight, however, the kite is not well adapted to work in light winds.

How further improved.—When the best general proportions of a given kite have been fully brought out as a result of exact and systematic measurements upon the behavior of the kite, it is my purpose to critically analyze the strains upon every member of the kite frame, and proportion the strength of each member to the strain it must bear. The whole structure of the kite is a system of connected trusses, the strains upon the several parts of which may be easily determined by the methods so commonly employed in the construction of bridges and similar framed structures. This method of analysis can not fail to result in an increase of strength and decrease of weight, as all material will be employed to the best advantage.

The longitudinal truss, made to the dimentions indicated on the drawings, has, in some cases, proved too weak. At the present stage of the investigations considerable attention has been given to finding the best proportions for the distances between the cells and between the surfaces of a single cell, also, the proper width of the cloth bands. Much valuable observational data has been obtained, but further information is needed before a definite conclusion can be stated. When the best length for the longitudinal truss of a given kite is definitely known, I think it will be an easy matter to greatly improve the construction of the truss so as to secure adequate strength with the minimum weight. Thus far the sticks of the rectangular frames have been made of the same size throughout, notwithstanding that it is plain not only that some frames on a given kite are under greater strain than others, but that different parts of the same frame receive very different strains.

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[1] The weight of the best and strongest kite thus far made is about 1.9 ounces per square foot of sustaining surface.

General remarks on constructions.—It may be added here that the improved construction while in fact very simple to a person with a few tools and gifted with real mechanical dexterity, does not claim to be of such a degree of simplicity that anybody can practice it. The novice with hammer and vise may be puzzled, for example, to neatly form the tin angle pieces shown in Fig. 53. Stringing the wire ties in the frame, just as they should be, may also prove perplexing. These operations take some time and require some skill, but when a cell is completed you have something that can stand the wind. The cloth is not going to work loose and give trouble after the kite has been flying an hour or two in a stiff breeze, neither will the symmetry of the cell be impaired. The original construction of such a kite requires a little more time than other forms, but it retains its efficiency and symmetry a longer time in the end, and, because of this latter quality is less likely to distort while flying and smash itself in a precipitate dash to the earth.

Aside from all these comments on the simplicity of construction, the object of paramount importance ever in the mind of the writer has been to secure the maximum attainable efficiency in the action of a given kite. Other things have been subordinate to this. The old-fashioned slide-valve steam engine, with fixed cut-off for example, is a marvel of simplicity compared with the complex, intricate, quadruple expansion engines of modern type, with balanced valves and automatic cut-off gear. What is the excuse for this complication?—efficiency. The improved engine will do twice the work, it may be, per pound of coal and barrel of water consumed. Just so with kites. One or two efficient kites, a moderate length of wire under an easy and safe-working tension, are all that are required to reach great elevations in fair winds. With kites of less efficiency to reach the same elevation, more kites, more wire, and far greater strains are necessary, increasing greatly both the danger of breaking the wire and the labor of winding it in. The incentive to fly kites to great elevations and thus excell all previous records is naturally very great. To do so on the principle that any kite is good enough so long as the result is attained, may be justifiable in the minds of some, but is hardly scientific. The writer believes that when kites of the maximum attainable efficiency are produced, and of which the strength and weight of the several members are duly and intelligently proportioned to the strains they must bear, just as is done in great bridges, only with far greater nicety, because with kites the factor of safety must everywhere be much smaller than with bridges—when these things are done, flights to astonishing elevations will follow easily of themselves and fewer reports will be read of kites breaking away with great loss of labor, wire, etc.

Characteristics of wing surfaces.—The cross-section of the wings of birds presents characteristics that are very different, as a rule, from those of a section of the surfaces ordinarily

employed in kites. As wings are evidently highly efficient sustaining surfaces, we may do well to analyze their form carefully and inquire to what extent and in what respect those forms may be copied with advantage in constructing kites. Aside from the arched form commonly characteristic of wings and which in the same wing probably varies more or less in amount with changes of pressure, we observe that the front edge is firm, rigid and thick, and that the wing becomes thinner and more flexible towards the rear edge, which is elastic and quite pliable under comparatively feeble forces. Much has been written concerning the advantages of these peculiarities by some who have sought to solve the mysteries of the sailing flight of large birds.

Without entering here into a detailed analysis of the action of the wind pressure upon a wing and its reaction thereto, I am convinced that the peculiar usefulness various writers seek to attribute to every detail of the wing structure is very much exaggerated and overdrawn. At least grave errors and misconceptions have resulted because a sharp distinction has not been drawn between the essentially different use of its wings made by the bird when employed in gliding or sailing flight on fixed wings, as contrasted with flight by flapping the wings.

The action of the wind upon the wings of sailing birds is similar in several respects to the action of wind upon kites whereas, nothing in the action of ordinary kites resembles the wing-flapping of birds. Therefore, whatever qualities of wing surfaces are of special advantage in sailing flight may also be of advantage in kite surfaces. By far the most important of these is the arched character of wing surfaces, the advantages of which have already been noticed. In addition to this we observe that the wing is thick on the front edge. It seems hardly possible that any other consideration than that of strength alone can determine what this thickness should be. If nature could make a wing of adequate strength but yet with a smaller sectional area, she would do so, and we believe it would serve the bird better. Again, the wing is also flexible so that the amount of curvature of its arched surface changes with different pressures. We are disposed to regard this as purely an incidental result. To have made a perfectly rigid wing, nature would have been obliged to make a heavier wing, which would be to the bird's disadvantage. The flexible wing is lighter, but yet of ample strength to resist the strains it may be called upon to bear. Although it can be shown that in wing-flapping-flight a slight advantage results from some flexibility, yet the same can not be shown to obtain to any important degree in sailing flight. We are forced, therefore, to the conclusion that for sailing flight the flexibility is an incidental quality. Finally, the thin, very flexible, feathers of which the rear edge of the wing is composed are believed to serve specially useful purposes in wing-flapping movements; but for sailing flight, in

which the wings are set at comparatively small angles of incidence, if there is any special merit in the characteristics of the rear edges at all, it is not to any appreciable extent due to their flexibility, but rather to the fact that the streams of air flowing over the upper and under surfaces are able to unite into one stream which is not broken up into objectionable eddies and whirls.

Kites with wing-like surfaces.—Grave constructional difficulties are encountered in giving to the sustaining surfaces of kites those qualities that we have pointed out as being advantageous in the wings of birds. In one of the kites framed in accordance with the improved plan of construction (fully illustrated and described on pages 47–50), the cloth was left free at the rear edge in order that the surface might be thin and pliable, like the rear edge of a bird's wing. This was accomplished by omitting the rectangular frames ordinarily forming the rear edges of the cells. The behavior of this kite in the air was, on the whole, very satisfactory. Nevertheless, the cloth formed into waves and fluttered to a greater or less extent, much as other kites having free edges of cloth had done. The kite was accidentally broken and the line of experiment was not carried any further. The dimensions of the kite are given in Table VI, No. 21.

Improved kite with arched surfaces.—Arching the sustaining surfaces of the improved kite is a matter of great simplicity. The cloth is simply left just a little slack between the two frames. Even when the cloth is fitted tight it will still arch upward to some extent when exposed to wind pressure. To make the depth of the arch about one-twelfth the cord requires, however, a slight looseness of the cloth between the frames. Thus far, I have made no effort to extend the arched effect to the side edges of the kite. The connecting sticks between the frames are straight. As a result the arched effect is most pronounced in the middle portion, gradually diminishing as the sides are approached, where it practically disappears. It is thus seen that in this kite the arched form of the surfaces can be secured without any additional material. When the first kite made of this form was flown in a moderately fresh wind the longitudinal truss was completely broken in two within ten seconds from the time the kite was launched. The break occurred at the point of attachment of the bridle and was caused, it is believed, primarily by the relatively greater pulling power of the arched surfaces. A very similar kite of greater area and with seemingly a more frail longitudinal truss was flown immediately afterward in fully as strong gusts of wind, but with no mishap whatever. When the broken truss was replaced by a stronger one the kite was flown with remarkable success in very light winds. In fact this kite flew when the wind was too light to sustain other cellular kites. Up to the first of July, however, no real test of the kite with arched surfaces had been made, owing to the lack of favorable opportunity.

Modified longitudinal truss.—When the truss is run through the inside of the cells, in the manner heretofore described, the slack cloth on the lower sustaining surfaces of the cells is partly prevented by the lower rib of the truss from forming the most effective arched surfaces. To avoid this difficulty the bottom stick of the longitudinal truss is arranged to come outside the cell, as shown in Fig. 57, which gives also the principal dimensions of the kite referred to in the foregoing remarks.

Other improved kites.—While the writer was engaged in developing and perfecting the construction of kites by means of the rectangular frames already described, Mr. Potter was working up certain modified forms of the cells. These were trapezoidal in form, rather than rectangular. In the first kite made each cell was provided with three, instead of two, sustaining surfaces. Long struts were used for spreading out the cloth surfaces. This involved cutting a rather large slotted hole in the middle surface of each cell to permit the passage of the diagonal struts. As a whole, the three-plane feature of this kite was not altogether satisfactory and was abandoned and a better kite constructed with simply a trapezoidal cell. This is shown in Fig. 58. The cell is spread by simply two long diagonal struts, instead of the four employed in the original Hargrave rectangle. This construction, with two long diagonal struts, was afterwards used for rectangular cells, also, and is recommended in preference to that shown in Fig. 50.

Points of advantage.—As already mentioned, the arrangement of struts adopted in the trapezoidal cell simplifies the construction considerably, with a slight gain in lightness at the same time. The side surfaces being set inclined considerably to the vertical contribute in a slight degree as sustaining surfaces. The weight of the kite per unit area is rather less than that of the rectangular cell of the same size. In contrast to these advantages the kite is imperfect in that there is nothing to prevent the cloth from fluttering, and the struts crossing within the interior of the cell offer some obstruction to the free flow of air through the cell. The oblique position of the side planes causes them to shelter in a slight degree the outer ends of the top surfaces, and it is believed there are more pronounced eddy effects in these corners than in the case of a cell of strictly rectangular form. The kites of this form appear to be the most steady and stable of any employed.

This form of kite is easier to make than kites of the frame construction, but although the latter are heavier the tests show they are superior, as will be brought out in a later section of this article, describing the results obtained.

The form of construction adopted in the trapezoid cell was also employed in making the rectangular cells. Prior to July 1 exact tests of the relative merits of the two forms had not been made, owing to the lack of favorable winds.

TABLE VI.—*Dimensions of Weather Bureau kite.*

Serial number.	Kind or shape of cell and material of covering.	Number.	Width of kite.	Height of cell.	Width of cloth bands.	Length of kite.	Actual surface of cloth.	Effective sustaining surface.	Total weight.	Weight per sqr. ft. sustaining surface.
			Ins.	*Ins.*	*Ins.*	*Ins.*	*Sq.Ft*	*Sq.Ft*	*Lbs.*	*Lbs.*
1	Rectangle, by struts, calico..	1	48	24	24.0	72	48.0	32.0	....	......
2	Malay, silk..................	....	68	....	....	60	16.2	......	....	......
3	Diamond, silk................	3	34	13	8.5	28	9.9	8.6	0.392	0.046
4	Kite, Fig. 41, cambric.........	1	80	....	9.0	54	16.2	14.6	2.51	0.172
5	Diamond, nainsook...........	1	65	22	18.0	60	32.5	29.0	2.14	0.074
6	Diamond, 5 cells, cambric....	1	65	18	8.5	78	37.9	35.3	....	......
7	Hunter, wing kite, muslin...		40	16	14.6	48	16.3	13.8		
	Each wing..................	1	23	....	......	40	3.2	3.2	1.55	0.077
	Total......................		....	....	......	......	27.2	20.2		
8	Kite, Fig. 42, cambric.........	1	33	....	15.0	45	26.5	......	....	......
9	Diamond, cambric.....	3	48	21	15.0	54	20.0	16.8	1.25	0.074
10	Diamond, 3 cell, cambric.....	1	48	21	15.0	93	30.0	25.2	....	......
11	Diamond, silk	5	40	17	13.0	43	14.4	12.0	0.91	0.076
12	Diamond, cambric............	1	40	17	13.0	43	14.4	12.0	1.20	0.100
13	Winged kite, silk.....		40	17	13.0	43	14.4	12.0		
	Each wing..................	1	23	....	......	43	3.5	3.5	1.14	0.067
	Total......................		...	....	......	......	21.4	17.0		
14	Wing kite, cambric...........		48	17	15.0	45	24.0	21.2		
	Each wing..................	1	48	....	......	60	12.0	12.0	2.31	0.051
	Total		....	....	......	......	48.0	45.2		
15	Silk kite, cambric wings.....		40	17	13.0	43	14.4	12.0		
	Each wing..................	1	38	....	......	64	8.4	8.4	1.51	0.039
	Total		....	....	......	......	31.2	28.8		
16	Hunter, cylinder kite, Fig. 48.		27	27	23.0	60	26.5	.....		
	Muslin, each wing............	1	34	....	.. ...	60	7.0	7.0	3.12	......
	Total......................		....	. ..	......	......	40.5	.....		
17	Diamond, cambric............	2	48	17	15.0	45	24.0	21.2	1.54	0.073
18	Diamond, cambric...........	1	60	24	15.0	45	32.0	27.1	1.98	0.073
19	Rectangle, by struts, nainsook........................	1	48	18	17.6	54	32.3	23.5	2.08	0.088
20	Rectangle, by frames, cambric	1	48	16	19.0	52	33.7	25.3	2.43	0.096
21	Rectangle, one frame per cell, cambric....................	1	51.5	14	15.0	60	27.3	21.5	2.21	0.103
22	Rectangle, 3 planes, cambric, Fig. 56......................	1	48	21	19.2	78	49.6	38.4	3.54	0.092
23	Ditto, reconstructed, with but two planes............	1	48	21	19.2	74	36.8	25.6	3.22	0.126
24	Ditto, with 3 planes	1	48	21	19.2	74	49.6	38.4	3.89	0.102
25	Trapezoid, 3 planes	1	...	....	......	......	......	......	....	......
26	Rectangle, by frames, paper..	1	60	13	19.2	60	39.2	32.0	....	......
27	Rectangle, by frames, cambric	1	48	16	19.0	65	33.7	25.3	3.04	0.120
28	Trapezoid, nainsook {top .... / bottom}	1	84 / 48	24	20.0	78	53.3	43.1	4.49	0.104
29	Trapezoid, nainsook {top .... / bottom}	1	80 / 48	24	18.0	54	46.4	36.7	3.06	0.083
30	Rectangle, by frames, cambric	1	60	20	19.2	70	42.7	32.0	3.59	0.112
31	Rectangle, by frames, cambric, cloth arched	1	60	13	19.2	76	39.2	32.0	3.34	0.104
32	Ditto, reconstructed.........	1	60	13	19.2	76	39.2	32.0	3.52	0.110
33	Rectangle, by struts, nainsook	1	48	21	20.0	72	38.3	26.7	2.80	0.105
34	Diamond, cambric............	1	30	13	9.6	33	8.0	6.6	0.374	0.057
35	Trapezoid, nainsook {top .... / bottom}	1	28 / 20	9	9.0	30	8.5	6.4	0.407	0.063
36	Rectangle, by frames, cambric	1	60	20	19.2	60	42.7	32.0	3.83	0.120

Explanation.—"Rectangle by struts," designates that the cell is a rectangle, and the form is given by means of a set of struts, such as shown in Figs. 50 or 59. "Rectangle by frames," designates that the rectangular cell is constructed as explained in connection with Figs. 51 to 55. The width of the kite is the crosswise dimension of the kite, that is, the dimensions at right angles to the direction of the flow of air

over the surfaces. In the case of the diamond kites, the width is not measured from side to side in a straight line, but along the surface of the cloth. The width, therefore, represents one-half the perimeter of the cell. An idea of the weight of the framework in the different kites may be obtained by comparing the weights per square foot of surface, with the following weights of materials employed in the covering:

	Pounds.
Weight of silk per square foot	.0084
Weight of nainsook per square foot	.0126
Weight of cambric per square foot	.0187
Weight of muslin per square foot	.0220

Bridle.—It was impossible to specify within the limits of the table the arrangement of the bridle on each kite. This was often changed with each experiment and will receive consideration hereafter.

The Weather Bureau Kites.—Table VI contains a schedule of the dimensions, weights, etc., of the greater part of the kites employed in the Weather Bureau experiments made between December 1, 1895, and July 1, 1896. Considerable care has been expended in the preparation of this table in order to give full and accurate information concerning every important element. In comparing the results obtained with kites of different form, and with different kites of the same form, the weight per unit of sustaining area is a most important desideratum. The weights of the finished kites were therefore always determined with care and are given in the table. It is strongly recommended that other experimenters, when publishing results of their work, be careful to give accurate data respecting the weight and the actual sustaining surface, so that a proper basis for comparison may be had. It will generally be best to give the total weight, rather than the weight per unit area, because the *effective* sustaining surface may not always be the same as the *apparent* sustaining surface. For example, a Malay kite 5 feet high and 5 feet broad appears to have a surface 12.5 square feet. When made in the usual way and with the cloth moderately taut, the lateral surfaces form a flat angle with each other, somewhat as shown in Fig. 34.

The angle at $C\ E\ D$ may sometimes be as much as 30° less than two right angles, and in such a case the sustaining effect of the 12.5 square feet will be no greater than that of about 12.1 square feet of surface not bent backward. Therefore, the true weight per unit of sustaining area in such a kite will be the total weight divided by 12.1 rather than 12.5. In other forms of kites more marked differences may arise. Some systematic method is therefore needed for accurately computing the effective sustaining surfaces of kites of different forms.

True and apparent angle of incidence.—Such a systematic method may be had by always taking account of the true angle with which the wind impinges against a surface in question. The distinction between the terms the *true angle of incidence* and the *apparent angle of incidence* will be understood from Figs. 60 and 61. With such a kite as shown in Fig. 60,

the surface is flat and continuous, the angle which the wind makes with the midrib of the kite, when flying normally, is clearly also the true measure of the angle with which the wind impinges upon the surfaces themselves. In this case, therefore, the angle $A\ O\ W$ is the *true angle of incidence.* If, however, the surface is bent backward across the midrib so as to form a dihedral angle, the kite will then appear as shown in Fig. 61. It is plain in such cases that the angle between the wind and the midrib is not the same as the angle between the wind and the planes themselves. Inasmuch as the angle between the wind direction and the surfaces themselves can not easily be measured directly, we will generally prefer to measure the angle between the wind and midrib (or some similar longitudinal axis of the kite) as *representative* of the true angle of incidence. In those cases in which the angle between the wind and midrib is not the same as the true angle of incidence of the wind, the former angle, that is, the angle $A\ O\ W$, will then be called the *apparent angle of incidence.*

It will be readily understood by those familiar with geometric principles that the true angle of incidence of the surfaces in such a case as represented in Fig. 61 will be the angle $A'\ O'\ W'$. $A'\ O'$ is the line formed on the kite surfaces by the intersection of a plane through $W'\ O'$ and perpendicular to the kite surface. It can be shown without difficulty that the angle $A'\ W'\ E'$ will always be the same as the amount by which the planes are bent backward, that is, it is the same as the angle $E\ D\ C$. The relation between the real and apparent angle of incidence may be found as follows:

Let $b =$ the angle $A'\ W'\ E' = E\ D\ C$.

Let $i =$ the *real* angle of incidence of the wind $= A'\ O'\ W'$.

Also let $a =$ the apparent angle of incidence $= W'\ O'\ E'$.

Then, by trigonometry—

$$\frac{W'\ O' \text{ sin. } i = A'\ W'}{W'\ O' \text{ sin. } a = E'\ W'} = \text{cos. } b.$$

$$\therefore \text{ sin. } i = \text{sin. } a \text{ cos. } b.$$

The angle b, as we have stated, is the amount by which the planes are bent backward, and therefore is always known, or can be found.

When comparing, for example, two such kites as the diamond cell and the rectangular cell, shown in Figs. 40 and 50, it is plain that when the midribs are set at the same angle in the air, the surfaces of the rectangular cell kite are inclined at a greater angle to the wind, and therefore experience a greater wind pressure than those of the diamond cell kite, shown in Fig. 40. To make a fair comparison between the kites, some allowance must be made, in the case of the diamond cell kite, for the slighter inclination of its surfaces. Similarly, in the trapezoidal kite, shown in Fig. 58, the side surfaces act as sustaining surfaces to some extent. We can compute the amount of this by the aid of the equation given above, as will be hereafter explained.

To make the proper allowance for different inclinations, we must know how much greater the pressure is at one inclination than at another. Different experimental researches have given different results on this point. Chanute,[1] after a critical analysis of all available data, has concluded that Duchemin's formula is probably the most accurate representation we have of the law of variation of pressure, with changes in the angle of incidence. This law, however, is strictly applicable only to plane surfaces. The law for curved surfaces is known to be very different from that for flat surfaces. As yet, however, no satisfactory statement of this law for curved surfaces has been formulated, so far as known to the writer. Since the surfaces are sensibly flat in most of the cellular kites described in Table VI, and as the angles of incidence of the surfaces in different kites will all fall within 15° of an average inclination, the use of Duchemin's formula will answer every purpose for the present.

If the pressure on a given plane surface placed normal to the wind is regarded as 100, then the percentage pressure, P, on the same surface inclined to the wind at an angle, i, will, by Duchemin's formula, be—

$$P = \frac{2 \sin. i}{1 + \sin.^2 i} 100.$$

The relative pressure upon inclined surfaces is of such importance in connection with the kite problem, that the value of P for such angles of inclination as are likely to occur in kite work are extracted here from Chanute's larger table:

TABLE VII.—*Proportional pressure on inclined flat surfaces.*

Inclination.	Proportional pressure.	Inclination.	Proportional pressure.	Inclination.	Proportional pressure.
°	%	°	%	°	%
1	3.5	11	36.9	21	63.7
2	7.0	12	39.8	22	65.7
3	10.4	13	43.1	23	67.8
4	13.9	14	45.7	24	70.0
5	17.4	15	48.6	25	71.8
6	20.7	16	51.2	26	73.7
7	24.0	17	53.8	27	75.2
8	27.3	18	56.5	28	77.1
9	30.5	19	58.9	29	78.6
10	33.7	20	61.3	30	80.0

In order to allow for the dissimilar conditions of the surfaces of the several forms of kites the effective sustaining surface for each kite has been computed on the basis that the midrib or longitudinal axis of the kite makes an angle of 18° with the wind. Numerous measurements have shown that such an angle is roughly an average angle found in practice. In the case of a kite with cells of rectangular form it is plain that when the midrib is set at an angle of 18° to the wind the surfaces are also at the same angle, and no allow-

[1] Progress in Flying Machines.

ance is necessary. If, however, we consider the diamond cell we see that when the midrib is at 18° to the wind the surfaces are at a less angle, and we therefore rate the kite as if its area was less in the same proportion as its lifting power is lessened by the slighter inclination of the surfaces. This is further elucidated by an example. Kite No. 17, of Table VI, is a diamond cell kite in which the cloth surface is actually 24 square feet. From the tabulated dimensions of the kite we find that the angle by which the surfaces are bent backward or forward from a flat surface is—

$$b = 20.7°$$

Assuming the apparent angle of incidence to be 18°, that is, $a = 18°$, we will have for the true angle of incidence—

$$\sin. i = \sin. 18° \times \cos. 20.7° = 0.2890$$
$$\therefore i = 16.8°$$

That is, when the midrib of this kite is inclined to the wind at an angle of 18° the surfaces are inclined at an angle of 16.8°. From Table VII the pressure on a unit area of surface at 18° is 56.5 per cent of the normal pressure, while upon the same area at 16.8° the pressure is 53.3 per cent of the normal. Multiplying the area of the kite by the ratio of the above pressures, we obtain—

$$24 \times \frac{53.3}{56.5} = 22.6 \text{ sq. ft.}$$

That is to say, the 24 square feet of surface in the diamond cell experiences a pressure, other things remaining the same, that is just equal to the pressure on 22.6 sq. ft. of sustaining surface on a flat surface kite, or, a kite with cells of the rectangular form.

We must notice further that the pressure on the inclined surfaces is not exerted upward, but is normal to the surface and assumes a laterally inclined direction, whereas, with surfaces not inclined in the manner under consideration, the pressure is exerted almost directly upward. These differences are shown in Fig. 62, which represents an end view of a trapezoidal cell. The pressure on the parallel surfaces may be represented by lines such as $O\ B$, $O'\ B'$, while on the side surfaces the pressure acts in the direction of the lines $L\ S$ and $L'\ S'$. The upward lifting effect of an inclined pressure, such as $L\ S$ will be represented by a line such as $L\ T$. In reality, the lines representing the effects mentioned above are not strictly in the plane of the paper, but are differently inclined thereto. We may, however, leave out of consideration as unimportant the effects arising from the lines being differently inclined to the plane of the paper, and, by doing so it results approximately that if P represents the pressure on a surface such as the side of the trapezoid, or the surface of a diamond cell kite, then the upward directed effect of this pressure will be—

$$\text{Upward pressure} = P \cos. b.$$

Where b, as before, is the amount the planes are inclined backward. From these considerations it follows that to ascertain the equivalent sustaining effect of the surfaces in the diamond kite, the proportional pressure on the inclined surfaces must be multiplied by the cosine of the angle we have called b. That is, in case of kite No. 17.

$$\text{Equivalent surface} = 24 \times \frac{53.3}{56.5} \cos.\ 20.7^\circ = 21.3 \text{ sq. ft.}$$

In other words the effective sustaining surface of the kite in question is 21.2 square feet, which means that this kite with 24 square feet of actual surface (other things remaining the same) will pull the same as a kite with rectangular cells in which the total area of the top and bottom surfaces is 21.2 square feet.

In a similar manner we may determine the sustaining effect of the steeply inclined side surfaces in the trapezoid cell. In the kite shown in Fig. 58, the total area of the side surfaces is 16.7 square feet. The angle between the side and top surfaces is 53.1°, that is, $b = 53.1^\circ$. Therefore, when the midrib of the kite is inclined 18° to the wind—

$$\sin.\ i = \sin.\ 18^\circ \times \cos.\ 53.1^\circ = .1854.$$
$$\therefore i = 10.7^\circ.$$

That is, the true angle of incidence of the wind upon the side surfaces is 10.7° when the mid rib is inclined 18°. By means of the ratio of pressures we have—

$$16.7 \times \frac{35.9}{36.5} = 10.6$$

That is, the total pressure on the 16.7 square feet is the same as the pressure on 10.6 square feet of the parallel surfaces of the kite. Introducing the further reduction necessary to resolve the pressure on the inclined surfaces to an upward directed pressure, we have—

$$10.6 \times \cos.\ 53.1^\circ = 6.36.$$

That is, the 16.7 square feet of inclined surfaces exercise, approximately, the same lifting effect as 6.4 square feet of the surface in the top and bottom planes of the cells. The total area of the top and bottom planes is 36.7 square feet. Adding to this the 6.4 square feet equivalent surface in the side planes, we have—

Total effective sustaining surface = 43.1 square feet.

The above computations are based on an assumed angle of incidence of the midrib of 18°. If some other angle, such as 12° or 25°, had been assumed, the result would still have been very nearly the same; and it will be found that it is not of great importance just what angle of incidence is assumed for the midrib. It is necessary only that some common basis of comparison be had for the several forms of kites.

General Results.—It is unnecessary to describe in detail the behavior and the comparative results obtained with the several kites described in Table VI. In the earlier part of our experiments appliances were not available, or had not been devised, by which the action of the kites could be critically analyzed and tested. The work consisted in flying the kites alone, or two or three in tandem to the highest attainable elevations, which were deduced from the known length of wire out, the measured angular elevation of the kite, and the inclination of the wire at the reel. Tests of this character are of very little aid in perfecting kites; about all that can be gained is a knowledge of the qualities of steadiness and general features of kite behavior, and added thereto a most valuable personal experience in the management of kites. In a subsequent section the methods of systematically analyzing the action of kites that were introduced later in the course of our experiments will be described.

Relative steadiness of kites.—The most perfectly made kite will never remain steady in one position for more than a few seconds at a time, but will always move about more or less, now rising or falling, swaying now to the right or left, now steady for a moment, etc. These constant changes in its position are directly caused by corresponding changes in the motion of the air itself. Above elevations of 600 or 800 feet, it will be noticed that a kite is always much more steady than for lower elevations, and it often happens that a kite which darts about violently near the ground flies quite steadily when 500 feet or more aloft. While the great and constantly recurring changes of the wind cause the irregular motions of the kite, yet the amount that a kite will move under a given change depends upon the nature of the kite itself. The cellular kites are all (I speak only of well made kites) much steadier than nearly flat single surface kites. Nevertheless, kites with cells of different proportions differ greatly in steadiness. Roughly speaking the greater the distance between the top and bottom surfaces of the cell the more stable and steady the kite. It was found that of the kites described in Table VI those were most steady in which the *total cloth surface* was relatively great, as compared with the *effective sustaining surface*. In the rectangular cells the side surfaces, under normal conditions, do not experience any sustaining pressure at all. These surfaces, however, act in the most beneficial way to prevent sudden and extreme sidewise movements of the kite. When a deep-celled rectangular kite experiences a sudden and momentary unequal distribution of pressure over its surfaces, the kite shifts its position much more slowly than a shallow-celled kite of the same kind. In many cases it no doubt happens that the sudden inequality of pressures disappears and equilibrium is restored before the kite has shifted its position by more than a part of the shifting which would have been required had not the kite been steadied by the action of the relatively considerable extent of side surfaces. Similar

effects are brought about in diamond kites when the short, or vertical diagonal of the diamond is relatively great. In the kite specified under No. 22, Table VI, and illustrated in Fig. 56, the middle plane of each cell could be removed. The kite always flew much steadier without the middle planes than with them. Large kites are more steady than small ones. Large kites were also found to be relatively heavier than small ones. The greater steadiness is no doubt, in part, directly a result of the greater mass, but the large kite experiences the average pressure of a considerable mass of air, which average pressure is no doubt less irregular than the average pressure of the very small stream of air intercepted by a very small kite.

The foregoing remarks apply wholly to well made kites. The darting and irregular movements of a kite which is defective in some respect are similar to those of a well made kite. The experienced kite flyer, however, is soon able to perceive when the motions are different from those caused by the usual variations of the wind, and therefore that something is wrong with the kite. The cause of erratic behavior in a kite known to be of good form may generally be traced to some lack of symmetry. It often happens that the defect exists in a pronounced manner only when the kite is under strain by the wind. Some weakness of the frame permits distortion when the strain exceeds a certain amount, and when the strain is removed the kite may appear to be all right.

Relative weights of kites.—The last column of Table VI gives the weights of the kites per square foot of sustaining surface. It is seen that very small kites, such as Nos. 3, 34, and 35, may be very light, nevertheless are quite stanch and strong. It will be shown further on that these small kites, notwithstanding the seeming advantage in weight, are less efficient than larger and heavier kites. The relative effects of edge pressures, waviness, eddies, etc., is believed to be large in small kites.

The winged kites were also very light in some cases, but experiments showed that these kites were entirely too weak, except for very light winds and that the frame work must be much stronger than that employed in the wing kites tested. Experience showed that, in general, stronger framing was necessary and the weight of the rectangle and trapezoid kites is noticeably greater than that of the diamond kites. The efficiency of these heavier kites was, however, in spite of the weight, greater than that of any others tested. The records of highest efficiency were obtained from kites Nos. 23, 29, and 36, which are the heaviest constructed. A light kite, even though less efficient, will attain a steeper angular elevation in a light wind than a more efficient kite of greater weight, but when the wind blows hard the inefficient kite increases its angular elevation but little, while, on the other hand, the efficient kite in a strong wind soars up to a high

angular elevation. Elevations of a mile or more cannot be attained unless there is plenty of wind, i. e., winds capable of producing pressures amounting to six or eight times the weight of the kite.

It is important that a clear idea be formed of the exact manner in which the weight acts as one of the forces that determine how high a given kite can fly. The effect of the weight under different conditions of wind force is brought out by the following consideration of the diagram of forces shown in Fig. 63. To avoid confusion of ideas and a complex diagram of lines, the drawing shows only the parallelogram of forces. We will also suppose for simplicity that the angle of incidence of the kite remains constant with different wind velocities. The line *A B* is drawn parallel to the longitudinal axis of the kite and represents its inclination; *H N* is a horizontal line; *O* is the point at which the lines of action of the wind pressure and gravity intersect. Let *O G* represent the weight of the kite. (The weight of the better grade of kites in Table VI ranged between .09 and .12 pound per square foot of sustaining surface.) Let us suppose our kite weighs 10 pounds per square foot. Now, with a light wind of between 8 and 10 miles per hour experimental results show that the pressure per square foot of sustaining surface in ordinary kites will be barely twice as great as the weight per square foot. The line *O Q*, twice as long as *O G*, represents such a relation between these forces, and their resultant is a force represented by the line *O R; O H* represents the direction the top end of the string must take. Under these conditions the kite on a short string can attain only a low angular elevation, represented by the angle *O H N*. If, however, the wind velocity were from 12 to 14 miles per hour, the pressure per square foot would be about double the former pressure. The conditions of equilibrium for such a case are given by the parallelogram *O Q′ R′ G*, and the string next the kite will take the direction *O H′*, which is very much steeper than its former direction, *O H*. It results, therefore, that the angular elevation of the kite has been greatly increased by only a small increase in the wind force. Let us next consider the effect of a still greater wind velocity, for example, 20 miles per hour. The pressure per square foot of surface for this velocity is fully ten times the weight of the kite per square foot. By constructing the parallelogram *O Q″ R″ G*, representing these relations, we locate the line *O H″*, which represents the direction of the string next the kite. The string in this case is only a little steeper than its former direction, *O H′*, notwithstanding that the wind pressure is considerably greater. With greater and greater wind pressures it will be found the direction of the string approaches closer and closer to the direction of the line *O M*, which represents the maximum possible steepness of the string. This degree of steepness could be attained if the weight of the kite were wholly inappreciable, or if the force of the wind were exceedingly

great compared with the weight. From this analysis we see that in light winds the effect of the weight of the kite is very detrimental and causes the kite to fly at a low angle of elevation. The same result will follow with a heavy kite in a heavy wind. That is to say, whenever the wind pressure per square foot is only two or three times the weight per square foot the kite can then attain only a low angle of elevation. On the other hand, when the wind pressure per square foot is five or six times the weight per square foot the kite can take nearly its maximum possible angular elevation, and even though the wind pressures increase to fifteen or twenty times the weight, only a very slight increase in the angular elevation will result. The effect of such pressures is expended almost wholly in increasing the tension on the kite string.

On the choice of materials in the construction of kites.—Two very important and interesting problems are presented under this head, namely: (1) What materials are best suited for kite building? (2) How may a given material be used to the best advantage? To these questions full and complete answers can not yet be given, they can be brought out only as the result of actual tests and trials of many materials and many plans of construction. Nevertheless we may be greatly assisted in reaching the best results by a careful consideration of what is already known concerning the strength and resistance of ordinary materials and certain general methods of construction.

(1) *What materials are best for kites?*—Silk is probably the lightest material for covering or sustaining surfaces, but it is not very durable, and like all kinds of cloth it is more or less objectionably affected by rain and moisture. A cloth kite in the rain or in a cloud becomes heavier unless the material has been varnished or otherwise rendered waterproof. The fabrics employed in balloon construction are both waterproof and impervious to the wind, but they are considerably heavier than the ordinary unprepared cloth as is shown from the weights given in table VIII. Very light balloon fabrics are manufactured of silk but these are not of sufficient strength to use for kites without being reinforced with some sort of netting. If we turn from textile fabrics we find that sheet aluminum is apparently the best suited of metals for kite coverings. In kites of the usual size it will probably prove to be impracticable to use metal in sheets thinner than one-hundredth of an inch (equal to three thicknesses of this printing paper.) Sheet aluminum of this thickness weighs 0.1414 pounds per square foot; sheet steel of the same size weighs .408 pound per square foot, but it much stiffer. Let us see how a kite of aluminum or steel will compare, in weight, with a cloth and wood kite. Kite number 23, of table VI, is the heaviest one listed except number 4, which was unsatisfactory. Sheets of aluminum riveted together in the form of rectangular cells 48 × 21 × 19.2 inches would require additional material to make the cell rigid. Moreover a

longitudinal truss is required to unite the cells. The wooden truss used in kite number 23 weighed just 0.664 pound, or at the rate of 0.0260 pound per square foot of sustaining surface. The aluminum kite would require a truss at least as heavy as this, and including the weight of the side surfaces of the cells but omitting any allowance for the additional framing required to stiffen the cells, the total weight of the metal kite with wooden truss would be 0.229 pound per square foot of sustaining surface as compared with a weight of 0.126 pound per square foot for the cloth and wood construction. If sheet steel were employed the weight of the kite would be 0.614 pound per square foot, still no allowance being made for framing required in the cells. These computations show clearly that these sheet metals can not be substituted for cloth in the construction of kites designed to attain great elevations. Very thin boards of white pine one-sixteenth of an inch thick would be a trifle heavier per square foot than the thin sheet of aluminum previously considered, and would probably require less framing to stiffen the cells. Such thin boards are likewise, however, too heavy for kite surfaces.

Aluminum wire gauze, the meshes of which are filled with elastic varnish, has been proposed for aerial planes. Such material is said to weigh from 0.094 to 0.250 pounds per square foot, according to the size of the wire and number of ends per inch.

Vulcanized fibers are a little less than half as heavy as sheet aluminum of the same thickness. Hard sheet rubber or ebonite and celluloid have practically the same density as the vulcanized fibers.

From these considerations we see that ordinary woven fabrics of cotton, either plain or treated with rubber or oil varnishes, must be given the first ranks as probably best suited of all available materials for kite surfaces. They are relatively inexpensive and can be had in a great variety of grades or weights.

Framing materials for kites must be chosen from among comparatively a few substances. Two or three different sorts of wood, aluminum, and steel make up the list. The material best adapted to a given use will often be determined by the kind of strain to which it is subjected.

(*a.*) *Tensile strength.*—A slender piece of steel wire, for example, is quite powerless to resist either flexure or compression, but no other substance compares with it in resisting tension. The tempered steel pianoforte wire employed for flying our kites resists breaking by tension at the rate of over 350,000 pounds per square inch. The same weight of aluminum of the very strongest quality would be broken by a strain of about 188,000 pounds. Aside from the difficulty of grasping it wood is also an excellent material to resist tension. Selected specimens from the strongest woods will sustain 220,000 pounds, whereas the same weight of fine tempered

steel will sustain 350,000 pounds. Wood subjected to tension is thus seen to be superior to aluminum, weight for weight. These comparisons are drawn between the very finest specimens of the several materials. Their respective merits stand in much the same relation, however, when we take the average specimens. Fine grades of ordinary steel for structural purposes possess a tensile strength ranging between 100,000 and 150,000 pounds per square inch. The same weight of the better grades of rolled aluminum bars sustain only about 80,000 pounds.

(*b.*) *Crushing strength.*—Steel is about eleven and a half times as heavy as ash and hickory, and about eleven times the weight of white oak, weight for weight. These woods, under compression, crush with strains of about 69,000, 77,000, and 103,000 pounds, respectively; similarly the light woods, white pine and spruce, crush at about 80,000 pounds. Aluminum, therefore, is strikingly inferior to ordinary steel and hickory, and is practically on a par with pine and spruce, at least as far as general strength is concerned, while the woods are probably superior as regards elasticity. Under tension woods are equal to the best grades of steel of tensile strength exceeding 150,000 pounds per square inch. Wood, however, can not be practically employed to advantage under tension.

These general comparisons of strength are instructive and very important, but we must also take into account some other factors upon which the suitability of a given material depends. While steel is so eminently superior to all other materials for light and strong construction, it can not be easily and cheaply procured in the appropriate forms nor in the small sizes required for use in the construction of kites of the ordinary dimensions. Even were steel of the desired form available, its use in small frames would prove troublesome and inconvenient, on account of the constructional difficulties in securely uniting and framing parts together when formed probably of tubes with very thin walls. For kites of very large size, however, steel is undoubtedly the lightest and strongest material available for the framework, while for kites of the ordinary sizes there is probably nothing so light and strong, so inexpensive and easily procured, or so readily worked into almost any form of framework as the ordinary grades of white pine and spruce. Bamboo is very light, strong, and elastic, but its application is seriously limited by its peculiar form, which admits of little or no variation without impairing the strength of the material.

The foregoing considerations leave little room for question as to which materials are best suited in general for kite construction. The weight and strength of the materials mentioned above are summarized in Table VIII.

The relative strength of the several materials is computed with reference to their weight as compared with that of steel. Thus, if the tensile strength of steel is 100,000 pounds per square inch of cross section, then the tensile strength of a

piece of aluminum of the larger cross section necessary to preserve the same length and *weight*, rated at 28,000 pounds tensile strength per square inch, will be 81,000 pounds. The sectional area of the aluminum bar will be 2.89 square inches.

Every designer of kites who wishes to attack his problem in a scientific and engineering manner will find a fund of valuable additional information concerning "The materials of æronautical engineering" in an article under this title by Prof. R. H. Thurston, of Cornell University, published in the Proceedings of the International Conference on Ærial Navigation, Chicago, 1893.

TABLE VIII.—*Weight and relative strength of materials.*

Material.	Weight, pounds.	Relative strength.	
		Tension.	Compression.
	Per sq. ft.	*Pounds.*	*Pounds.*
Silk	.0084		
Nainsook	.0126		
Lonsdale cambric	.0187		
Muslin	.0220		
Light silk balloon fabric (for models)	.0076		
Light cotton balloon fabric	.0218		
Regular balloon fabric, cotton	.0420		
Sheet aluminum 0.01 inch thick	.1414		
Sheet steel 0.01 inch thick	.408		
Aluminum wire gauze, fine	.094		
Aluminum wire gauze, heavy	.250		
Vulcanized, fiber 0.01 inch thick	.065		
Hard rubber, per each 0.01 inch thick.	.063		
Sheet celluloid, 0.01 inch thick	.064		
Tempered steel pianoforte wire		325,000-400,000	
Hard spring phosphor bronze wire		106,000-150,000	
Aluminum wire		87,000-188,000	
Cable laid twine		84,000-109,000	
	Per cu. ft.		
High grade steel, bars	490	100,000-150,000	
Aluminum bars	169	81,000	
Ash	43	114,000-171,000	52,000- 91,000
Hickory	43	114,000-160,000	91,000-112,000
White oak	43	114,000-........	63,000- 91,000
White pine	29	51,000-127,000	51,000-101,000
Spruce	31	79,000-158,000	71,000- 95,000

NOTE.—The relative strengths in the above table were compiled from Thurston's tables.

(2) *How given materials are best employed* in the construction of kites is a very interesting point, and will next receive a brief consideration. We have already been led to the conclusion that wood (white pine or spruce) is probably the best and most available material for the frame work of kites of moderate size. The strength of a given piece of material depends very much upon the manner in which it is strained. The principal strains that are likely to occur are lateral bending and compression. Shearing and torsional strains may also exist in some cases. Comparatively slight forces are sufficient to break a stick by flexure whereas the same stick will sustain far greater forces which tend to compress it. In devising the strongest and lightest construction, we must, therefore, avoid as far as possible subjecting the material to lateral bending strains. By a well known artifice of

construction, it will nearly always be practicable to substitute for large bending strains two other forces or strains. One of these will be compression, the other tension. Thus the slender stick, *A B*, Fig. 64, supported at each end, is unable alone to sustain any considerable load distributed over its length. If, however, a short column, *C*, and the tension members, *T T*, be introduced, the character of the strains are entirely changed. The stick *A B* and the column *C* will now be under compression, while *T* and *T* will be put under tension by loading, and the strength of the devise is enormously increased, as every one knows. The stick is still subjected to bending strains at points between the extremities and the foot of the column *C*, but the accumulated strains on a section and its length are both half as great as in the case of the whole bar, circumstances that contribute in still greater proportion to increase the strength.

This artifice of the truss is of unlimited application in kite construction where lightness and strength are so important. The principal strains in the frame work will by this means be compression and tension, the former sustained by wooden trusses the latter by slender wires, whose weight will generally be of very little importance. Wires of hard drawn phosphor bronze resist corrosion by moisture, etc., better than steel and will in many cases probably be preferable to steel which is very much stronger.

A wide field is open for the display of ingenuity in devising the best methods of working out the details of construction, that is, the best arranged forms of the several parts, how to conveniently and securely unite them, etc., remembering always that the frame work must possess that happy quality, uniform strength. The final solution of these difficulties can not be stated yet. The writer has endeavored to point out a few important principles and has indicated the lines along which it seems the work may best proceed, but many ingenious minds by repeated experimentation must achieve new improvements before it can be said that the best has been attained.

EFFICIENCY.

Hitherto no exact and scientific methods appear to have been employed to determine the relative merits of different kites, or to fully measure and analyze their action. Experimenters in general have been contented to make a rough estimate by eye of the angular elevation attained, or if this has been measured the results, with rare exceptions, have been inaccurate, and the observations limited to a very small number. Often, probably, but a single reading has been made at a favorable moment when the kite had momentarily attained an extreme elevation. Moreover, the observations have generally been made with the object of ascertaining the altitude of the kite when a long length of deeply sagging line was out. Little or no notice appears to have been given to the effect of the long line in modifying the angular elevation of the kite.

If any accurate measurements of the behavior of kites have been systematically made such measurements have, with one or two exceptions, been conspicuously absent from any published accounts of kite experiments known to the writer. It is therefore impossible to form any estimate of the relative merits of the kites employed by different individuals. Eye observations without the aid of instruments suffice to determine only general qualities of steadiness, etc. Those factors upon which the usefulness of a kite for meteorological purposes depends, namely, the *lift* and *drift*, can be determined accurately only by aid of instrumental measurements. Eye estimates of the angular elevation of kites tend nearly always to exaggerate the amount of the angle, and data of this sort respecting the behavior of kites can have no place in scientific investigations.

Various methods of expressing numerically the merit of a given kite may be employed. The *lift* and *drift* may be made the measure of excellence of a given kite. But the *lift* and *drift* of a kite vary with every gust of wind, and it is difficult to deduce from these quantities a true numerical rating of the merit of a kite under examination. This objection to the use of lift and drift as a measure of excellence would have less weight if the wind blew with a steady direction and constant force, but this is never the case. Moreover the *lift* and *drift*, aside from depending directly upon the force of the wind, depend further upon both the actual surface of the kite and upon the angle of incidence. A very perfect kite which happened to be bridled in such a fashion that the angle of incidence was, for example, 25°, would, in all probability, show a smaller lift and a larger drift than a much inferior kite bridled so that its incidence was 15°. This difference of incidence would, in all probability, wholly escape the notice of an ordinary observer unless his attention was specifically directed to discover it. Even if discerned with the eye the real numerical relation could be established only by carefully made instrumental observations. The *lift* and *drift* in themselves, therefore, do not constitute a suitable basis for a true numerical estimate of the useful effect available in a kite. They are in fact only conventional and derived ideas. We must go back of them to the fundamental forces from which they are derived for the basis upon which true comparisons can be made. *Efficiency* is the technical term widely employed in all branches of engineering to designate numerically the useful effect available in machines of any sort. Thus, we have the efficiency of a steam engine, of a boiler or furnace, the efficiency of electric generators, motors, converters, etc., so likewise we may have the efficiency of kites. This measure of merit, as adopted at the Weather Bureau for the comparison of kites with each other, is based upon fundamental mechanical principles, and is widely applicable to any kind of kite. The resulting measure is not directly dependent upon the angle of incidence of the kite or upon the direction or force of the wind.

Efficiency of kites.—The basis upon which any rating of efficiency is deduced is very largely a matter of choice. In dealing with machines and appliances for producing physical or mechanical effects, economical considerations have much to do with the ultimate or absolute utility of the devices employed. From the economic standpoint an efficiency rating is an exceedingly complex result, depending upon many factors of the most heterogenous character — cost of space, wages of employees, cost of transportation, interest on investment, etc. These factors can be related to each other only in a highly arbitrary and empirical manner. The efficiency of mechanical devices, as the term is ordinarily used, is not generally deduced upon the economical basis but depends upon purely mechanical and physical considerations of cause and effect. Dismissing economics we will likewise define the efficiency of kites upon the physical and mechanical basis. Even here, choice may be made among several methods. We may consider that the most efficient kite is one which can attain the highest elevation. As we shall see hereafter, the elevation attained by a kite is purely a question of the forces acting upon the string. It is very plain that to make the efficiency of a kite depend in any way upon the string is not desirable. Even if we eliminate, as we may, effects due wholly to the string, and make the efficiency of the kite depend upon its power to attain elevation, we still make a bad choice, for we would thereby fail to consider that kites may be employed for other purposes than attaining elevations. A highly efficient kite from such a standpoint would be highly inefficient if it were employed to pull sleds or carry a line ashore from a stranded vessel.

A basis upon which the efficiency of a kite can be deduced, that is not open to such objections as raised above, may be had by considering only the *inclination of the total resultant wind pressure* to the surface of the kite. A kite, fundamentally, is a surface either plane or curved against which it is designed the wind shall press. The ideal kite is that surface; the actual kite is a material substance having thickness, edges, possibly a tail, etc. The string is an entirely separate accessory not necessarily included in discussing efficiency. In the analysis of the action of the wind upon surfaces a principle of efficient action was pointed out on page 42, as follows: "*The condition of ideal efficiency* (*that is, an efficiency of* 100 *per cent*), *in the action of the wind upon thin plane surfaces, obtains when the total resultant pressure is exactly normal to the surface.*" Recognizing that a kite is a surface against which the wind shall press, we say broadly that the pressure is most efficiently exerted when for plane surfaces the total pressure is exactly normal to the surface. For arched surfaces we must deal with inclinations to a tangent, or more conveniently to the chord of the arch. We will speak of this more in detail further on.

The reader who has followed the section on the "Analysis

of forces acting on kites" (page 28), and who has in mind the effects of the weight of the kite in depressing it, as set forth on page 64, is prepared to readily understand the application of the above-mentioned principles to the derivation of the efficiency of a kite. Under ideal conditions, that is, conditions in which edge pressures, surface or skin friction, waviness and fluttering, eddy effects, etc., are wholly absent, it follows as a direct consequence of the principles already established that the ideal kite, whose weight is considered inappreciable as compared with the wind pressure, will fly in such a manner that the direction of the string next the kite will make an angle of 90° with the surface of the kite or with the longitudinal axis thereof. In the case of an actual kite of appreciable weight and more or less imperfect in other respects, it will be found upon measurement that the direction of the string next the kite will make an angle of less than 90° with the longitudinal axis. This angle between the direction of the string next the kite and the longitudinal axis of the kite is properly made the numerator of the efficiency ratio, and for convenience and brevity we will call it hereafter the *efficiency angle.* It is the angle $A\ O\ R$ in Fig. 65. If, upon measuring the angle between the direction of the wire and the kite, it were found to be 75°, for example, then the efficiency of the kite would be given by the ratio of this angle to 90°, that is,

$$\text{Efficiency} = 75 \div 90 = 83\tfrac{1}{3} \text{ per cent.}$$

This measurement relates specifically to the *position* the kite takes in the air, and does not deal with the *pull* of the kite. We might, therefore, more specifically call the above defined efficiency the *position efficiency.* The *pull* is a factor wholly independent of the *position* when we consider simply the mechanics of a kite, and it is well to keep these factors separate in estimating the merits of kites.

The different positions that kites of different efficiencies assume when flying from a string which is either so light or so short that it does not sag to an appreciable extent is shown in Fig. 65. $A\ B$ represents the midrib or longitudinal axis of a kite; and the string is supposed to make an angle of 75° therewith, corresponding to a position efficiency of $83\frac{1}{3}$ per cent. The angle of incidence of the horizontal wind with the kite is supposed to be 20°. In such a case the angular elevation of the kite will be 55°. If, however, the kite were perfect, in which case the efficiency angle would be 90°, the position the kite would then take is shown at $A'\ B'$, and its angular elevation would be 70° instead of 55°, the kite still retaining the same angle of incidence of 20°. It might be argued that by changing the angle of incidence of the kite $A\ B$ by the proper amount without changing its efficiency it would fly as high as $A'\ B'$. This may be true, but the more efficient kite would pull harder, and if *its* angle of incidence were likewise

changed, the perfect kite would again fly higher than the imperfect kite and pull equally hard.

The foregoing treatment of the question of the position efficiency of kites applies strictly only to plane surface kites, and throughout all preceding discussions where efficiency angles have been measured in reference to a midrib or longitudinal axis of the kite it has been assumed, as was generally the case in the Weather Bureau kites, that the *apparent angle of incidence* was also the *true angle of incidence.* If this is not at least approximately so in a given kite, or if, as in a trapezoidal kite, the sustaining surfaces are at different angles of incidence, then the efficiency angles must be taken in reference to the planes themselves.

Arched surfaces.—When we deal with arched surfaces some experimental results show that the wind forces in question do not act in the same manner as upon plane surfaces, and while the general principles involved in deducing efficiency still remain the same, a slight change in computing it numerically will probably be required, owing to the fact that in the ideal case the string might form with the longitudinal axis an angle—$A\ O\ R$, Fig. 65—greater than 90°.

The difficulty in the case of arched surfaces is that we do not know, a priori, the maximum possible angle between the string next the kite and the surfaces, or the chord of the arc; that is, we have no certain value for the denominator of the efficiency fraction. Some observations show that the angle ought to be greater than 90° in the ideal case, but just how much greater is not known. This is a matter which is at present of minor importance. In fact, this angle undoubtedly varies with every modification of the curvature of the arch, and possibly with changes in the angle of incidence. While, therefore, we may not be able to arrive at a mathematically correct numerical value of the *efficiency ratio* in the case of arched surfaces, we still have in the *efficiency angle* alone a wholly satisfactory basis for numerically rating the merit of any kite, whether with flat or with arched surfaces. The most efficient kite, other things remaining the same, is the one showing the maximum efficiency angle. The experiments up to July 1 had not been carried sufficiently far to show the most satisfactory procedure in the case of arched surfaces. The foregoing remarks refer to the *position efficiency* of kites. Let us consider briefly the pulling power of kites.

Pull.—In comparing the pulls of different kites, the comparison must, of course, be made always for the same conditions; that is, for the same velocity of the wind, the same angle of incidence, and the same unit of surface. There is very little reason why kites should differ much in the pull per square foot of surface if we have been careful to measure the sustaining surface upon a systematic basis, in some such manner as that already described on pages 57–61. The following appear to be the principal causes why one kite should pull more than another under otherwise similar conditions: Arch-

ing the surfaces of the kites, as we have already explained, may increase the pull very greatly. In kites of the cellular type the sheltering of one surface by another may diminish the pull per unit area, more or less. The pervious character of ordinary cloth may serve to diminish the pull. The wind may not press to good advantage upon the pointed lateral and bottom extremities of such kites as the Malay, and the pull may be less in consequence.

Efficiency—how determined.—Having defined the mechanical significance of the efficiency of kites, the next point is how shall the necessary measures be made in order to compute the efficiency in a given case. The only quantity which it is necessary to measure is the angle between the wire and the kite. It would not be difficult to construct a small recording instrument which, when connected between the bridle and the main wire, would produce a continuous record, from which the angle between the main wire and one of the bridle lines could be deduced. Since the angles between the bridle and the kite may always be known, the record mentioned would suffice completely to give the desired efficiency angle. This sort of an instrument could be combined with a small dynamometer recording the pull of the kite upon the same record sheet with the efficiency angle. If still further combined with a recording anemometer, the resulting apparatus would constitute a complete *kite indicator*, since it would give the principal elements required in working out the efficiency of kites and the action of the forces thereon. It was not considered advisable to attempt to introduce such an instrument for recording the elements mentioned, although the matter received serious consideration, and the dynamograph portion of the instrument for recording the pull of the line, either at the kite or at the reel, was actually constructed. This instrument is shown in Fig. 68 and is described on page 79.

Incidence scale.—In the absence of the instruments required for making the above described automatic record of the efficiency angle, another method was devised for measuring by eye observations, not only this angle, but the angle of incidence of the kite and, simultaneously, its angular elevation. This method is best explained in connection with a kite with rectangular cells. By aid of a stencil made from a sheet of oil-board paper a series of graduation lines 1 inch apart are boldly marked in black upon the white cloth of one of the upper sustaining surfaces of the cell, usually the forward cell, as shown in Fig. 66. The lines are one-quarter inch broad, and each fifth line is about 2 inches longer at each end than the intermediate lines, which are about 4 inches long.

The zero line of the scale is at the front edge of the cell. Figures need not be applied to any of the lines, as the grouping in fives renders the reading of the scale sufficiently easy and certain. The scale, for convenience, may be called the incidence scale, since by its use we ascertain the angle of incidence of the kite.

When a kite of the usual proportions provided with such a scale is flying in a normal manner, and is viewed from a position near the reel, a part only of the incidence scale is visible, the remainder being concealed behind the lower surface of the cell. At a distance of a few hundred feet the number of divisions of the scale exposed to view can be read with the unassisted eye, but in our regular experiments a small reading telescope, such as employed by physicists for reading galvanometer scales, etc., has been used. The telescope for the purpose was mounted upon an ordinary engineer's tripod. Easy motion in both altitude and azimuth was provided, and in the absence of a regular vertical circle an accurately divided draughtsman's protractor was arranged to give the angular elevation of the axis of the telescope. Assisted by the telescope, readings of the incidence scales have been made with as much as 2,000 feet of wire out, but in order to eliminate from the observations as much as possible the effect of the sag in the wire, which had to be taken into account in the manner hereafter described, observations were nearly always made at distances of between 400 and 1,000 feet.

The protractor was divided to half degrees, and readings of less than this amount could be made. Owing, however, to the constant and great changes of the position of the kite, refinement in angular readings, when working at short range, possess no significance. For the same reasons the estimates of the incidence scale were confined in general to half inches. To offset the coarseness of these measures observations were repeated at intervals of from 30 to 60 seconds, and ten or more readings made in each set from the mean of which the final deductions were made.

The act of making an observation consists in bringing the kite in view in the telescope, and following its motions until at a favorable moment a reading of the scale can be satisfactorily made with the kite near the center of the field. The inclination of the telescope at this moment is the angular elevation of the kite, which is thus determined simultaneously with the scale reading. Fig. 67 shows the relation of the angles in question. The angle A at the kite is the observed angle of elevation; i is the desired angle of incidence; the angle x is given by the equation:

$$\tan. x = \frac{s}{h}$$

in which h is obtained from the known height of the cell and s is the reading of the incidence scale.

Finally, $i = 90° - (A + x)$.

If we were justified in neglecting the sag in the wire, then the efficiency angle between the wire and the kite would be,

Efficiency angle = elevation + incidence.

Generally, however, we will desire to be more accurate than to neglect the sag in the wire. The data for making the neces-

sary allowance for the sag of the wire is obtained if, at the moment the scale reading is made with the telescope, an assistant observes the inclination of the wire at the reel. In a subsequent section the mathematical equations of the curve assumed by the kite wire will be discussed at length, and it will be shown that when the sag in the wire at the reel is known the sag next the kite can be found. For the present we will call these angles S' and S, and they are so marked in Fig. 67. With the kite at a distance of 400 feet or more from the reel, lines of sight, such as $R\ V$ and $R\ V'$, will be sensibly parallel, although they are not so in the drawing, owing to the exaggerated size of the kite. In practice, observations are made only when the sag in the wire is slight, in which case the angles S and S' are nearly equal to each other. Owing to the peculiar character of the curve assumed by the wire, the angle S will be smaller than S' as a rule. The efficiency angle, including the sag, is

$$A + i + S.$$

Inclination of wire at reel.—As stated above, the sag of the wire is obtained from a measurement of the inclination of the wire at the reel. This was measured by means of a protractor, arranged to hang over the wire with its diameter parallel thereto, and provided with a light hand or index pivoted at the center of the arc and always assuming a vertical direction, thus serving to indicate on the graduated arc the angle of inclination of the wire. This angle subtracted from the angular elevation of the kite, measured from a point carefully chosen just at one side of the reel, gives the angle S'. In strong winds the position of the index of the protractor was sometimes affected, and it was necessary to weight the index with a small plumb-bob. Finally, the whole protractor was inclosed in a glass case.

Probable errors.—By means of the telescope and incidence scale simultaneous observations of the angular elevation and incidence of the kite are made in a highly satisfactory manner. Owing to the great variations of the wind the incidence is found to vary considerably, as also the position of the kite. Observations must be made quickly and at favorable moments. The measurement of the incidence angle is less accurate in proportion as the scale reading is small. An error amounting to a whole inch in a single reading of the scale can not be made except by gross mistake, and the error of the mean of several readings is probably less than 0.5 of an inch. The corresponding error in the angle, under conditions found in practice may, in extreme cases, be as much as 2°. Repeated observations of the same kite on different days have been so consistent with each other that it is believed the errors are actually less than those just described. If a satisfactory measure is not obtained in the manner described it is necessary simply to move the telescope back from the reel a short distance, so as to obtain such an angle of

view as $T\ T'$, Fig. 67, resulting in more accurate measures. If efficiency tests are to be made at the same time, then an additional measurement of the angular elevation of the kite from a point near to and at one side of the reel will also be required.

General remarks on efficiency.—The manner we have chosen for deducing the efficiency of a kite is such that the weight of the kite is a modifying factor, causing the efficiency to be less than would be the case if the efficiency were made to depend only upon such imperfections as edge pressures, skin friction, waviness, eddies, etc. To include the effect of the weight with that of the imperfections just mentioned is, we believe, a very proper course, inasmuch as the kite must first sustain its own weight before it is available for rendering useful services. Moreover, if for analytical purposes it is desired to study separately the imperfections mentioned above, the precise knowledge we may always have of the weight of a kite enables us, by the aid of simple mechanical principles and the resolution of forces, to perfectly separate the effects due to weight and other disturbing influences, so that each may then be studied separately.

Efficiency modified by weight, eddies, etc.—The modifications produced in the direction of the string next the kite, due to the weight of the kite and different wind velocities, were fully pointed out on page 64. We now notice also that every change in the angle of the string means a corresponding change in the efficiency angle, which is the angle $A\ O\ H$, $A\ O\ H'$, $A\ O\ H''$, etc., Fig. 63. From a consideration of these points we see that owing to effects arising from its own weight the efficiency of a kite in light winds is less than in heavy winds. In Fig. 63 it was assumed that the direction of the resultant pressures $O\ Q$, $O\ Q'$, $O\ Q''$, etc., corresponding to increasing wind forces, remained always at the same angle with the kite surface. This will be the case when the influences due to edge pressures, waviness, eddies, etc., follow exactly the same law of increase as obtains for the normal wind pressure. This seems likely to be the case with edge pressures, perhaps, but it is probable that the detrimental effects of eddies and fluttering are proportionally greater at high than at low velocities. It may, therefore, happen that a kite seriously defective in respect to these last-mentioned imperfections would, with moderate wind forces, show increasing efficiency up to a certain point, but that in still stronger winds the efficiency would actually become less. In other words, *the strong wind would seem to blow the kite down.* Such an instance has not come within my own observation, but its probability is easily seen from a physical standpoint.

Incidence and efficiency.—The pressure of the wind upon the kite may be feeble, not alone because of light wind velocities, but also by reason of the kite flying at small angles of incidence. If the incidence is made too small the pressure of the wind even at considerable velocities will be only a relatively

small multiple of the weight, and this condition, as we have found, results in only small angular elevations. There is, in fact, a particular incidence giving a maximum effect. This is treated of further on, in the section on the catenary.

Ascending air currents.—Thus far it is assumed, in computing the incidence and efficiency of kites, that the wind flows in horizontal streams. This is generally, but not always, the case. It is well known that masses of air generally have a descending or ascending as well as a horizontal motion. Under these circumstances the actual direction of motion of the air may be in lines that are upwardly inclined to an appreciable extent. Kites are very sensitive to such conditions and the action of such ascending currents causes the kite to soar up to an unusually high angular elevation. The keen observer will not be misled into believing, as some have, that the phenomenal behavior of a kite under such influences is due to some peculiar excellence of the kite itself. These effects of ascending currents were well known and understood by the scientific kite flyers of half a century ago. A brief quotation in regard thereto is cited on page 3, mentioning the experiences of the Franklin Kite Club.

If a kite flying normally in a horizontal wind assumes an angle of incidence of, say 15°, then in an ascending current flowing in a direction inclined upwardly at an angle of 10° the same kite would seem to assume an angle of incidence of only 5° and would soar to a point near the zenith, although still flying at an angle of incidence of 15°.

When the bridle adjustment of a kite remains fixed, the angle of incidence of the kite will also remain constant with a given wind force. Even with different wind forces, unless they are very feeble, the incidence will change, but very little. Furthermore, the efficiency angle of a given kite is a definite angle, which must remain nearly constant in the same kite so long as it is not modified in any way or the wind force is not too feeble. Since, as we have just seen, the incidence and efficiency angles of a kite must be constant with given conditions, it necessarily results that the angular elevation will also be constant. When, therefore, we have fully established the constants of a given kite by careful measurements under normal conditions of longitudinal air motion, the behavior of the kite under abnormal conditions of ascending currents is, perhaps, one of the best measures we have of the amount of the abnormality. By means of a kite with its constants carefully determined, it thus seems possible to measure, with a fair approximation, the upward inclination of movements of masses of air otherwise quite inaccessible.

Causes of small efficiency.—We have found that when the wind pressure is several times the weight of the kite the influence of the weight on the efficiency angle is very small and unimportant. Results obtained with good kites under favorable conditions show that efficiencies of 90 per cent and over may be attained. When, therefore, we find,

under favorable conditions of wind, smaller efficiencies than this, we know at once that the kite is either excessively heavy or defective in respect to edge pressures, waviness, eddies, etc., or the angle of incidence is too small, which latter is easily corrected by changing the bridle adjustment. An incidence of 15° is probably as small as can be employed with advantage, at least with flat surface kites. In the case of cellular kites, if the top and bottom surfaces are too near each other, or if the front and rear cells are too close together, the flow of the air through the structure of the kite may be, as it were, choked up to a greater or less extent. All such effects will have a direct influence on the efficiency.

From these brief remarks it is evident that in dealing with efficiency we have a powerful and searching artifice for numerically and justly expressing the merit of a given kite. It is hoped experimenters will familiarize themselves with the principles involved and apply them in general to kites of their own, so that some idea can be had of the real duty that a given kite has performed.

GENERAL OBSERVATIONS OF KITES.

While the measurements of the angles referred to in the preceding section are sufficient to establish the angle of incidence at which a given kite is flying, and to determine its position efficiency, still other observations are needed to ascertain all the facts we wish to know concerning the behavior of the kite. Among these the following are discussed:

Measurement of the tension of the wire.—Prior to July all measurements of tension of the wire at the reel consisted of eye readings of a spring scale attached to the reel in the manner described on page 24. The scale of the dynamometer employed embraced 50 pounds, and when the tension on the wire was greater than this limit a purchase (in the mechanical sense) was obtained by use of a movable pulley, the dynamometer being attached to one end of the cord passing over the pulley. This tackle, as is well known, multiplies effects by two; hence, the dynamometer which indicates normally only 50 pounds answers for a maximum strain of 100 pounds.

Dynamograph.—Fig. 68 represents a small dynamograph devised to give an automatic record of the tension of the wire. The clock is one of the very small, inexpensive house clocks on sale by any jeweler. But very little alteration is required to mount the clock on its hour-hand axis, which, being suitably prolonged, is clamped firmly in the bearings *A A*, with the result that the whole cylinder containing the clock revolves at the rate of one revolution per hour. In order to reduce to a minimum the motion of the moving parts concerned in measuring the tension, the spring employed is exceedingly stiff, being one of the excellent springs commonly used in steam engine indicators. A strain of 100 pounds compresses the spring about one-sixth of an inch. This mo-

tion is magnified and recorded with precision by the pen in a manner readily understood from the figure. The dynamograph in its original form was designed for use with small kites with pulls of not to exceed 35 pounds, whereas experiments were actually made requiring a greater range of scale. The necessary modifications in the dynamograph to adapt it to larger scales were not, however, made until after July 1.

Measurements of wind velocity.—No direct measurement of the wind velocity was made during the kite experiments except the continuous records made at the Weather Bureau. These records answered every purpose so far as the general experiments were concerned, but a much more specific and local measurement is greatly needed in order to formulate the laws connecting the pressures per unit area with the angles of incidence, velocity of wind, perviousness of cloth, character of kite, etc. A small anemometer weighing only 0.8 of a pound has been constructed which records, not by the usual step by step methods, but continuously every movement of the cups. Fractions of a mile at their true momentary velocities are fully recorded by it and momentary velocities for very brief periods have been deduced with the same accuracy as is attained in ordinary velocity measurements. This instrument was, however, not available for use until after July and its further description is reserved to accompany the publication of results we hope to attain by its use.

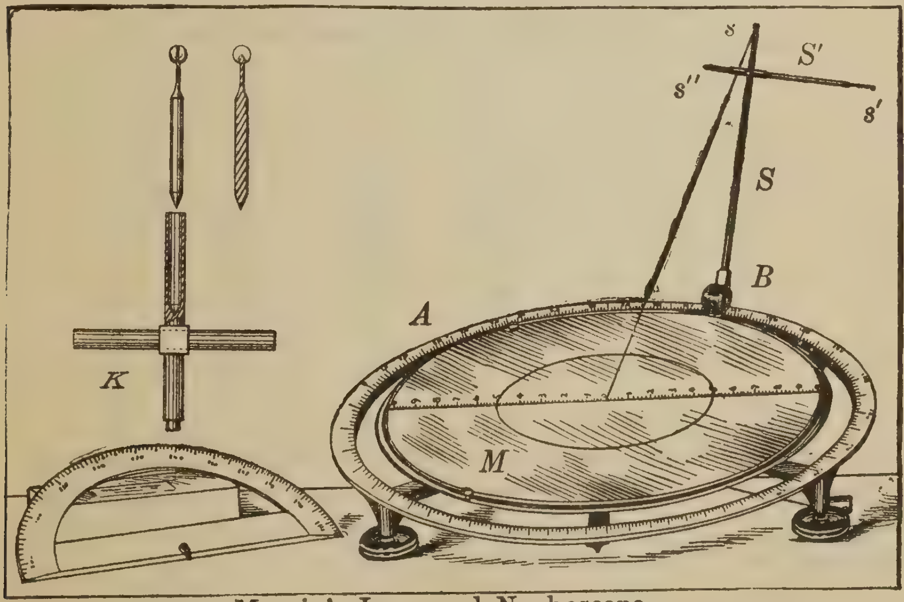
Measurements of angular elevation.—The manner of measuring the angular elevations of kites by aid of the telescope, as described in the section on efficiency, is not the most convenient when nothing but the angular elevation is needed nor is its accuracy all that can be desired in the case of lofty ascensions. Two other methods have therefore been employed.

Nephoscope.—It was often desired to ascertain the average position of a kite without observing necessarily its efficiency. Owing to the constant changes going on in the angular elevation of the kite the average must be based on numerous measurements made momentarily and at perfectly equal intervals of time. The best results are secured if the instrument employed admits of being read or at least set at a precise instant of time. This is the case with the nephoscope employed by the Weather Bureau for observing the positions and motions of clouds. It is shown in the illustration below and was described at length in the WEATHER REVIEW for January, p. 9.

Its manipulation is so simple that scarcely more than one second is required for ascertaining the angular elevation of a kite. The nephoscope is mounted upon a firm table or support near the reel and the mirror *M* carefully leveled by the aid of an ordinary level which accompanies the instrument. To observe the kite the eye is placed so that the former is seen reflected from the central spot of the mirror, and the sighting knob *s* on the staff *S* set so that the knob is also seen reflected at the center of the mirror. This setting can be

made in a very short time. The angle of the inclined thread may then be measured with the protractor, and we have the angular elevation of the kite. Such settings of the nephoscope were generally made at exact intervals of thirty seconds for a period of five to ten minutes. The average of ten or twenty readings of this sort may be considered to give a close measure of the average position the kite under examination will take under ordinary conditions of atmospheric motion. Experimenters should not be satisfied with a less exact and truthful record of the average performance of a given kite than one obtained in some such way as that described.

Sextant.—The nephoscope answers admirably for the measurement of angular elevation under most circumstances. In the case of lofty ascensions, however, the kite appears very tiny and is sometimes difficult to see. In order to measure the angular elevation accurately under such circumstances a sextant fitted with a low-power glass has been employed. A small plate-glass mirror about 12 inches square, mounted on three leveling screws, was used in place of the ordinary artificial horizon of mercury. The accuracy of this method of measuring the angular elevation is really more than demanded. It was not necessary to read the vernier of the graduated scale at all, as sufficient accuracy was attained by eye estimation of the minutes of the scale. By the optical principles involved in the use of the sextant with an artificial horizon the actual scale-reading gives double the angular elevation. At great heights the apparent position of a kite varies but little, nevertheless our practice has been to read angles at comparatively short intervals, so that a fair average position may be attained.



Marvin's Improved Nephoscope.

Calculation of height.—When the sag in the wire is disregarded the altitude of the kite is given by the equation:

$$H = r \sin. A.$$

Where r is the length of wire out and A is the angular elevation of the kite. This assumes that the length of a straight line from the reel to the kite is the same as the length of the wire itself, which of course can not be true. If, however, the sag in the wire is not over 20° at the reel, then roughly the straight line will be only about 2 per cent shorter than the wire. For a sag of 30° the difference will be about 4 per cent. The height, computed by the equation given above, should then be diminished by the proper percentage allowance for sag. Results obtained in this way will be quite as accurate as by more complicated methods of deducing the height by triangulation or by records of air pressure obtained from barographs attached to the kites. Other accurate methods of computing the height will be given in a subsequent section on the properties of the catenary, including the case of invisible kites.

RESOLUTION OF FORCES.

When the efficiency angle and pull are known for a given kite, also the bridle adjustment, we have the data for constructing a complete diagram of the actual forces acting on the kite. By way of illustrating more in detail how the analytical observations on kites have been conducted in the Weather Bureau investigations, and to show how the diagram of forces is constructed and the resolution of forces carried out in an actual case, the following observations from our field notebook are given:

Tests of kite No. 30, *May* 19, 1896 (*see Table VI, p.* 56).

[Bridle adjusted as shown in Fig. 69; observations made with 700 feet of wire out.]

Time. p.m.	Pull.	Incidence scale.	Inclination of wire.	Elevation of kite.
h. m. s.	*Pounds.*		°	°
2 4 15*	20	2.5	....	60.5
2 8 20	20	3.5	56.0	57.5
2 9 20	25	3.5	57.0	60.0
2 10 45	4	6.0	50.0	61.0
2 11 30	20	3.2	54.0	57.0
2 13 00	20	3.0	55.0	58.0
2 13 50	22	4.5	56.0	57.5
2 14 30	24	4.0	57.0	60.5
2 16 20	16	3.8	56.3	59.0
2 18 20	15	4.0	56.0	59.5
2 20 00	14	4.0	55.0	56.5
2 22 20	10	6.0	51.0	55.0
....	24	5.0	54.0	55.0
Means....	17.8	4.21	54.8	58.0

*This first observation, being incomplete, is omitted in taking the sums and means.

Results.—The height of the cell of this kite is 20 inches; therefore, the scale reading, 4.21, corresponds to an angle x given by the equation

$$\tan. x = \frac{4.21}{20} = 0.2105 \text{ whence } x = 11.9°.$$

Hence, the incidence = 90° − (58.0° + 11.9°) = 20.1°.
Sag of wire at reel = 58.0° − 54.8° = 3.2° = S'.

When the sag of the wire is small, as in this case, a close approximation to the sag at the kite, that is, the angle S is given by taking $S = 81\%$ of S', therefore $S = 2.6°$.

Hence, the efficiency angle $= 58.0° + 20.1° + 2.6° = 80.7°$.

$$\text{Whence the efficiency} = \frac{80.7}{90} = 90\%.$$

This kite was observed later on the same day both by the telescope and nephoscope with 2,000 feet of wire out. The readings are given below.

Time. p.m.	Pull.	Incidence scale.	Inclination of wire.	Elevation of kite.
h. m. s.	*Pounds.*		°	°
3 44 10*	12	7	35	50.5
	23	6	45	52.0
	28	5	46	55.5
	18	5	46	58.0
	26	4	50	54.0
	30	4	50	54.0
	8	5	48	55.5
	24	5	45	52.5
	18	4	44	52.5
3 49 00*	18	5	47	53.0
Means....	20.0	5.0	45.6	53.75

* Time of only first and last observations noted.

From these observations $x = 14.0°$; incidence $= 22.2°$; $S' =$ sag at reel $= 8.2°$; $S = 6.6°$; efficiency angle $= 82.6°$; efficiency $= 92\%$.

From observations with the nephoscope the following results were obtained—2,000 feet of wire out:

Time. P. M.	Pull.	Inclination of wire.	Elevation of kite.
h. m s.	*Pounds.*	°	°
3 54 00*	16	42.0	52.0
	14	42.5	51.5
	10	46.0	53.5
	8	42.0	55.0
	16	41.0	51.5
	16	44.0	51.5
	8	40.0	52.5
	16	41.0	49.5
	10	47.0	55.0
	8	39.0	54.0
	12.2	42.45	52.60

* Every 30 seconds.

If we assume, as we are justified in doing, that the average incidence of the kite was the same as actually observed in the observations made a few moments before we shall have, incidence assumed to be 22.2°, sag in wire at reel, $S' = 10.2°$; $S =$ approximately $8.1°$; efficiency angle $= 82.9°$; whence the efficiency $= 92\%$.

We have given above three separate sets of observations. The amount of variation in the efficiency angle that may be looked for under such conditions is shown in the three values, 80.7°, 82.6°, and 82.9°.

The pull on the wire was measured at the reel where it is less than the tension at the kite. The difference between the two will depend upon the relative inclination of the wire at kite and reel. The mathematical relation between the tensions at different points on the kite wire does not concern us at the present moment and is reserved for treatment in a subsequent section.

Diagram of forces.—Fig. 70 shows the actual diagram of forces corresponding to the results obtained from the first set of observations. The center of gravity of the kite is at the center of figure as at g. Passing a line through F so as to intersect the axis of the kite at the efficiency angle, viz, 80.7°, we have the line $L\ F\ O\ R$ which is the action line of the resultant of all the forces at the kite. To resolve this total resultant force into its components we draw a vertical line, $g\ O$, through the center of gravity of the kite and lay off thereon from O downward the line $O\ G$, representing on a convenient scale the weight of the kite=3.59 pounds. From properties of the catenary it can be shown that when the tension of the wire at the reel is 17.8 pounds as observed in the present case the tension at the kite under the observed conditions will be 21.1 pounds. This force is represented by the line $O\ R$ drawn to the same scale as $O\ G$. Completing the parallelogram of which $O\ R$ and $O\ G$ are the diagonal and one side, respectively, we have the line $O\ Q$ which represents the total resultant of all the wind pressures upon the kite. By measurement we find this resultant to be 24.2 pounds and by prolonging its action line downward we find that it intersects the kite at an angle of 85.1°.

We wish now, from this diagram, to arrive at some idea as to the relative intensity of the wind pressure upon the front and rear cells of the kite. The front cell is freely exposed to the wind, while the rear cell is in some degree sheltered, and we may reasonably expect to find the pressures on the latter deficient. When we wish to represent by a single force the combined effect of the wind pressures upon both the upper and lower surfaces of a cell, the principles of mechanics lead us to locate the point of action of that single force midway between the surfaces, provided the upper and lower pressures are equal. If they are unequal, then the point of action must be proportionately nearer the greater force.

Now, in such a kite as that under consideration the upper and lower surfaces are separated by a distance a little greater than their width. In such a case it is believed the upper surface at ordinary wind velocities can not be sheltered to any large extent by the lower surface, and that the pressures on the two surfaces are sensibly equal, at least in so far as concerns the interference of one surface with the other. Nevertheless, in the case of the rear cell it is quite probable that the exposure of at least the upper surface is far from unobstructed, and the pressure of the wind upon the lower surface also may be slightly deficient by reason of the prox-

imity of the front cell. Therefore, it is probable that the points of action of single forces representing the combined pressures upon the upper and lower surfaces of the cell can not with accuracy be placed midway between the surfaces; but our present purposes do not require that these points be located with great accuracy. It can be shown that little or no sensible error will be produced in the results we seek if we assume, as we shall, that the points of action of the single forces in question fall midway between the upper and lower surfaces of each cell, as, for example, upon the line *C C* in Fig. 70.

Returning now to the resolution of the forces, we found from the diagram that the line *O Q* represented the total wind pressure upon the kite. This force is made up of the pressures upon the individual cells, and we have just found that the points of action of the pressures upon the individual cells may be assumed to fall upon the line *C C*. In accordance with the principles of mechanics, the point of action of the total resultant pressures will also fall upon the same line, *C C*. The point, in fact, will be at the intersection of the lines *O Q* prolonged, and *C C*; that is, at *O′*, and the total resultant is completely represented by the line *O′ Q′*. This force, as just stated, is the resultant of two forces, one being the wind pressure upon the forward cell, the other the corresponding pressure upon the near cell. Since the sustaining surfaces in the cells are equal, the wind pressures ought also to be equal, under the assumption that one cell does not shelter the other. Our diagram of forces enables us to discover the difference in the pressures on the two cells. To prevent confusion of lines, we will use in this study the diagram in Fig. 71, which represents the line *C C* of Fig. 70, and the force *O′ Q′*. Before we can divide the force *O′ Q′* into the two parts representing the wind pressures upon the front and rear cells, respectively, we must locate the centers of pressure in those cells. We can not do this very accurately, but the points of action of the forces are undoubtedly forward of the middle of the cell in each case. Several formulæ based on experimental work have been given for computing the position of the center of pressure on a rectangular plane surface, and if we employ one of these we can not go very far astray. Chanute in "Progress in Flying Machines," gives the formula $d = l\,(0.2 + 0.3 \sin. i)$. Applied to the present case, l is the width of the cloth bands in the kite under consideration, and i is the angle of incidence; d is the distance from the front edge of the surface to the center of pressure. Computing the result, we find $d = 5.8$ inches. By this method we locate the center of pressure in each cell at *P* and *P′*. Through the points thus found we draw the lines *P N* and *P′ N′* parallel to *O′ Q′* and proportional to the lines *O′ P′* and *O′ P* respectively. According to the well known principle of the lever, two forces represented by the lines *P N* and *P′ N′* will be exactly equivalent to the single force *O′ Q′*, and *vice versa.*

That is to say, if $O' Q'$ is known, then the forces $P N$ and $P' N'$ are those sought, and represent the forces on the two cells respectively. $P N$ is a pressure of 18.5 pounds, while $P' N'$ is only 5.67 pounds, which shows to how great an extent the rear cell is sheltered by the forward cell. If we assume that the action of the wind upon the forward cell is unimpeded and acts sensibly with the maximum effect, then the rear cell experiences only 31 per cent as much pressure as the front cell. In other words, the efficiency of the rear cell is only 31 per cent. These results depend in a manner upon an assumed position of the center of pressure within the cells. But any other logical assumption that one may desire to make concerning the position of the center of pressure will lead to results that do not differ greatly from those found above, and a noticeable disparity between the pressures upon the front and rear cell will still exist. If the center of pressure is placed nearer the center of each cell than we have assumed, then the disparity will be greater. If it is placed at the extreme front edge of the cell, which would be absurd, there would still be some disparity.

We see from the foregoing example, in which the resolution of the forces acting upon a kite have been worked out in detail, that the diagram of forces is a most powerful means of analysis. It has been the aim in the Weather Bureau investigations to exhaustively analyze the action of kites in the manner outlined above and thereby arrive at the best possible forms and proportions. With the limited time and means available for constructing kites and for preparing the apparatus and accessories required in making the observation, only partial solutions have thus far been reached, although the most gratifying improvements upon the original forms have even thus been effected. The line of study and experiment described above is better calculated to lead to improvements in kite flying than the simple flying of kites to just as great elevations as they can attain carrying meteorological instruments with them at the same time, so as to obtain atmospheric records. It is impossible by this latter method to analyze the action of the kite or to discover any except the most tangible and conspicuous imperfections. All the finer details leading to the development of the best forms and proportions of kites must always remain beyond the grasp of such experiments. Table IX contains the results of the efficiency tests made upon kites up to July 1, 1896.

Bridle adjustment.—The adjustment of the bridle of the kite is not a matter of so much mystery and importance as is often supposed to be the case. It will be found, if proper experiments are made, that very much the same results can be obtained by the greatest variety of bridle arrangements, or even by discarding the bridle altogether. In the case of the kite shown in Fig. 70, exactly the same results would have been obtained if the bridle had been discarded and the wire attached directly to the kite frame at the point S. This,

at least would be the case if there were no fluctuations in the wind, and its force and character had corresponded to the average of the observed variable wind. Likewise any one of many other forms of bridles, such as suggested by the several dotted lines in the diagram, might have been employed. The only condition which each of these arrangements must satisfiy is that the point of attachment of the wire must fall upon the line *L O*.

TABLE IX.—*Results of efficiency tests.*

Date.	Kite. No.*	Kite. Kind.	Number of observations.	Amount of wire out.	Angular elevation of kite.	Inclinat'n of wire. At reel.	Inclinat'n of wire. At kite.	Incidence at kite.	Efficiency angle.	Efficiency.	Pull.
					Φ	θ'	θ	i	D		t
1896.				Feet.	°	°	°	°	°	%	lb
March 26...	22	Three planes.	10	1,000	52.6	48.1	56.2	21.0	77.2	86	.....
April 28.....	24	....do.........	10	1,000	41.2	31.9	48.8	25.6	74.4	83	.....
May 11	24	....do.........	4	400	56.1	53.8	58.4	23.8	82.2	91	26
May 11......	24	....do.........	10	400	57.6	54.0	60.5	23.8	84.3	94	27
May 15	24	... do.........	5	1,000	59.0	55.6	61.6	15.8	77.4	86	12
May 15......	24	....do.........	10	1,000	61.0	57.1	64.2	16.0	80.2	89	15
April 22...	23	Two planes..	6	400	55.3	51.1	58.7	23.9	82.8	92	.....
	23	....do.........	10	400	59.1	54.9	62.5	21.4	83.9	93	.....
April 21.....	28	Trapezoid....	12	290	56.0	53.7	58.3	16.3	74.6	83	.....
April 21.....	28	....do.........	10	1,000	49.6	44.8	53.5	17.6	71.1	79	.....
April 22.....	28	....do.........	5	400	57.7	55.0	60.4	17.8	78.2	87	.....
April 30.....	28	....do.........	9	1,000	53.4	48.9	57.1	14.9	72.0	80	.....
May 11......	28	....do.........	10	400	56.4	54.5	58.3	15.6	73.9	82	27
June 11.....	28	....do.........	10	571	48.2	45.3	50.5	19.0	69.5	77	28.2
June 11.....	28	....do.........	10	571	50.5	47.2	53.2	15.1	68.3	76	22.9
May 11 ...	19	Rect. struts..	14	400	46.6	41.9	50.5	17.9	68.4	76	8.6
	19	....do.........	10	400	53.9	48.5	58.3	17.9	76.2	85	8.4
April 28.....	29	Trapezoid....	10	1,000	45.0	36.7	51.7	18.3	70.0	78	.....
June 11.....	29	....do.........	10	571	53.5	50.0	56.3	15.5	71.8	80	31.1
June 11.....	33	Rect. struts..	7	571	48.8	44.0	52.7	22.8	75.5	84	10.7
June 11.....	35	Trapezoid ...	5	....	46.7	40.0	53.4	14.7	68.1	76	3
May 19....	36	Rectangle....	12	700	58.0	54.8	60.6	20.1	80.7	90	17.8
	36	....do.........	10	2,000	53.8	45.6	60.0	22.2	82.2	91	20.0
	36	....do.........	10	2,000	52.6	42,4	60.2	22.2	82.4	92	12.2

* The kites in this table have the same numbers, respectively, as the corresponding kites in Table VI.

Steadiness in position.—We have said there would be no differences arising from the use of any of the several arrangements of bridles suggested, provided there were no fluctuations in the wind. We may go still further and say that although the extreme positions of the kite corresponding to variations of the wind might differ considerably, depending upon the bridle, yet it is quite probable that the averages would still be much the same. The complete analysis of this element of the kite problem is comparatively complex and a few important points only will be brought out here.

In the first place we have to deal with a highly complex set of variations of the wind. It will answer in the present discussion to consider only variations affecting considerable masses of air, such that the whole kite is subjected to uniformly changed conditions that persist long enough, at least, to permit the kite to assume a new position of equilibium. These variations may be divided into two groups: (*a*) variations of direction, (*b*) variations of force. In treating of the variations under (*a*) we must consider not only the incessant

changes in horizontal direction, but must also recognize and deal with similar changes that are likewise going on in an up and down sense. The motions of considerable masses of air may be either upwardly or downwardly inclined as well as horizontal.

The variations of force are of great complexity, but their general character is pretty well known to every observer and need not be detailed here.

Changes of horizontal direction.—The changes in horizontal direction of the wind cause the kite to shift from side to side. So long as we tie the bridle only to the midrib of the kite, as is nearly always done, at least with the malay and cellular kites, all sidewise tiltings of the kite must take place about that stick as the axis. It does not matter, therefore, so far as these tiltings are concerned, how the arrangement of the bridle may be changed in other respects. In their direct effect on the sidewise movements of the kite all bridles are the same so long as they are fastened to the same stick or midrib.

Variations of force and direction.—Variations of either force or direction of motion, if inclined upward or downward, tend to cause the kite to rise or fall. If the variation is only of the inclination of the direction of motion of the wind, then the new position of equilibrium for the kite flying on a short and straight string will differ from the old by an angular amount (if measured from the reel) sensibly equal to the change in the inclination of the wind's motion. These angular changes would be exactly equal if it were not for a secondary effect, due to the weight of the kite, that need not be now considered. For such variations of direction as just considered the arrangement of the bridle in a particular case can not have any direct influence on the behavior of the kite.

If the variation is one of wind force, then the bridle adjustment may have much to do with the amount by which the kite will change its position. When the force of the wind is considerable, variations of the force will cause but slight changes in position of the kite, however bridled. When the force is only moderate, variations thereof produce larger changes in the position of the kite, and in such cases the following statements set forth rather crudely certain results depending upon the bridle. When the bridle is short, that is, when the point of attachment of the main line is relatively close to the surface of the kite, the angular changes in the position of the kite depending upon variations of wind force will tend to be greater than when the bridle is longer. Discarding the bridle, which can be done in cellular kites, gives a minimum distance between the point of attachment and the front surfaces, and is apt to result in large changes in angular elevation of the kite when the force of the wind falls off greatly. With short bridles, the angle of incidence of the kite tends to be more nearly constant with different wind velocities. Being nearly constant, the variations of pressure upon the kite will be nearly as great as those of the wind;

whereas, the longer bridle permits the angle of incidence to increase when the velocity of the wind diminishes, in consequence of which the variations in the pressure upon the kite are less than the variations in wind force.

A very long bridle may produce conditions under which it is impossible for the kite to be in equilibrium.

The writer is accumulating numerical data by which the most useful proportions and disposition of the bridle in a given case can be fully established. As yet these studies have not been sufficiently advanced to justify more detailed statements than given above.

With a given form of bridle (preferably one in which neither of the angles next to the kite is a right angle), the angle of incidence of the kite will be made *smaller* if the point of attachment of the main line be shifted toward the *forward* end of the kite, and *vice versa.*

Lofty ascensions.—The favorable conditions of wind have been generally employed for the purpose of conducting those analytical studies of kite behavior which we believe to be the most helpful in developing the kite; yet efforts have been made, from time to time, to reach great elevations, either with a single kite or a tandem of two or more. Opportunities with favorable winds are, however, infrequent in Washington. Detailed observations of a few of the more successful high ascensions will give an idea as to what kites of the kind employed may be expected to do. These results are grouped in Table X.

TABLE X.—*Details of special ascensions.*

Date.	Time.	Angular elevation of kite. Φ'	Inclination of wire at reel. Θ'	Length of wire out. l	Approximate height. $l \sin \Phi'$	Remarks.
1896.	*h. m. s.*	° ′	° ′	*Feet.*	*Feet.*	
Jan. 27	....	43 00	38	1,300	886	Single diamond kite No. 5; 29 square feet surface; wind favorable at first, but gradually died out; pull from 20 to 24 pounds.
	....	35 30	17	3,490	2,027	
	....	28 47	....	4,834	2,328	
	....	28 45	....	4,894	2,354	
	....	34 15	....	3,767	2,120	
	....	38 38	....	2.273	1,419	
Feb. 10	....	34 7	....	3,844	2,156	Tandem of No. 9, 16.8 square feet; 200 feet below, No. 12, 12 square feet; 200 feet still lower, No. 5, 29 square feet; fair wind; total surface, 57.8 square feet.
	....	37 20	....	3,844	2,331	
	....	39 45	....	4,696	3,003	
	....	34 10	....	5,782	3,247	
	....	29 55	....	7,262	3,622	
Mar. 26	....	52 36	....	1,000	794	The first reading is the mean of ten made for measuring the incidence of kite, = 21.0°. These are the first incidence measurements made in the Weather Bureau experiments. Single kite; three-plane rectangular cells, No. 22, 38.4 square feet; wind very favorable; pull from 8 to 16 pounds with 3,975 feet out, and from 20 to 26 pounds with 6,010 feet out, showing considerable increase of velocity with elevation; inclination of wire at reel not recorded, but exceeded 10°.
	....	36 15	....	3,975	2,350	
	....	34 00	....	"	2,223	
	....	41 32	....	"	2,635	
	....	43 10	....	"	2,719	
	....	42 35	....	"	2,690	
	....	33 30	....	6,010	3,317	
	....	30 40	....	"	3,065	
	....	30 15	....	"	3,028	
	....	30 40	....	"	3,065	
	....	31 35	....	"	3,148	
	....	34 28	....	"	3,400	
	....	36 5	....	"	3,540	
	....	36 45	....	"	3,596	

TABLE X.—*Details of special ascensions.*—Continued.

Date.	Time.	Angular elevation of kite. Φ'	Inclination of wire at reel. Θ'	Length of wire out. l	Approximate height. l sin Φ'	Remarks.
1896.	*h. m. s.*	° '	° '	*Feet.*	*Feet.*	
Mar. 26.	....	33 50	....	6,010	3,346	
	....	34 20	....	"	3,390	
	....	34 40	....	"	3,418	
	P.M.					
Apr. 30	1 29 30	53 24	48 54	1,000	803	
	1 36 15	45 42	....	1,000	715	
	2 15 00	61....	....	2,000	1,749	
	15 30	59....	....	"	1,714	
	16 00	57....	....	"	1,677	
	16 30	57 30	52....	"	1,687	The first and second observations are the means of ten readings made upon trapezoidal kite No. 28; 43.1 square feet of surface; the incidence was 14.9°; 700 feet from the first a second trapezoid, No. 29, 36.7 square feet, was attached on 150 feet of line; total surface, 79.8 square feet. The wind was not very favorable during these experiments, and it was with difficulty the second kite was started.
	17 00	58 30	52 30	"	1,705	
	17 30	56....	50....	"	1,658	
	18 00	55....	50....	"	1,638	
	18 30	55...	50....	"	1,638	
	19 00	54 30	49....	"	1,628	
	19 30	56....	48....	"	1,658	
	2 42 30	43 48	30....	4,000	2,769	
	44 10	46 50	31....	"	2,918	
	44 45	45 30	32....	"	2,853	
	45 20	45 59	30....	"	2,876	
	45 50	45 48	31....	"	2,868	
	46 35	46 5	30 30	"	2,880	
	....	46 47	28 30	"	2,915	
	47 10	46 23	26 30	"	2,896	
	49 21	45 21	21....	"	2,846	
	49 50	43 25	20....	"	2,749	
	50 48	40 41	21....	"	2,608	
	51 30	42 23	31 30	"	2,696	
	52 20	45 5	31 30	"	2,832	
	3 00 45	38 30	....	5,000	3,112	
	3 5	39 25	22 30	"	3,175	
	3 45	39 45	23....	"	3,197	
	4 20	40 5	22....	"	3,220	
	5 10	40 34	25....	"	3,252	
	5 48	41 8	26....	"	3,290	
	6 35	41 57	25 ...	"	3,342	
	7 10	41 25	20....	"	3,308	
	8 5	39 30	21....	"	3,180	
	8 50	39 9	22....	"	3,157	
	3 17 40	33 40	17....	6,000	3,326	
	18 45	35 50	16 30	"	3,512	
	19 30	36 32	15....	"	3,572	
	20 5	36 59	16....	"	3,610	
	20 45	37 30	16 30	"	3,653	
	....	38 12	16....	"	3,710	
	22 20	38 30	16....	"	3,735	
May 28	2 34 00	41 35	....	6,430	4,268	Tandem of two kites. Three-plane kite No. 24, 38.4 square feet surface; two thousand feet lower down the trapezoid, No. 28, was attached, 43.1 square feet. The wind was just about right. The sky was partly overcast with clouds, and towards 3 p. m. it became apparent that a thunderstorm was likely to come up. The electrical discharges from the wire were very sharp, and followed each other in rapid succession, producing sparks an inch or more long. Means were not available at the time for measuring the pull, and the inclination of the wire could not be measured with the device usually employed, owing to the unpleasant effects from the electric discharges.*
	34 30	42 00	....	"	4,303	
	35 00	42 5	....	"	4,310	
	....	43 20	....	"	4,413	
	36 30	44 10	....	"	4,480	
	37 30	44 15	30 +	"	4,487	
	2 43 20	42 45	....	7,236	4,912	
	44 20	39 15	....	"	4,578	
	45	37 00	....	"	4,355	
	46	37 20	....	"	4,388	
	46 45	38 55	....	"	4,546	
	49	43 15	....	"	4,958	
	....	43 42	....	"	5,000	
	....	44 30	....	"	5,072	
	2 50 30	45 32	....	"	5,164	
	....	46 36	....	"	5,258	
	....	48 7	....	"	5,387	
	3 2 00	30 50	....	9,219	4,725	
	....	29 28	....	"	4,535	
	....	29 40	....	"	4,563	
	....	30 45	....	"	4,714	
	....	34 55	....	"	5,277	
	....	37 55	....	"	5,665	
	....	37 48	....	"	5,650	
	....	45....	....	9,000	6,364	

TABLE X.—*Details of special ascensions.*—Continued.

Date.	Time.	Angular elevation of kite. Φ'	Inclination of wire at reel. Θ'	Length of wire out. l	Approximate height. $l \sin \Phi'$	Remarks.
1896.	*h. m. s.*	° ′	° ′	*Feet.*	*Feet.*	
May 28	....	45 30	....	9,000	6,419	
	3 15....	46....	....	"	6,474	
	....	46 45	....	"	6,555	
	....	46 00	....	"	6,474	*

* The group of observations made with 9,000 feet of wire out represent the height of the base of the gathering clouds within which the kite was frequently obscured. About half past three p. m. a very severe thunderstorm burst upon us, and we were obliged to seek shelter. The kites continued to fly for several minutes during the storm, but finally broke loose. The storm was one of the most violent that has ever been known in Washington, and much damage was done throughout the city to roofs of houses, etc. A lofty steel flagstaff at Fort Myer, near the point at which the kites were flown, was bent over by the force of the wind at an angle of about 45° at the point about 50 feet above the ground, where it was held by guys. The kites were both found the same afternoon at a distance of 15 miles due east of the point from which they were flown. Neither kite had been damaged by the storm, and both are still in good condition.

THE KITE LINE.

Thus far in the study of the behavior of kites and in the analysis of the forces acting thereon we have considered, with few exceptions, only the kite itself. We now wish to study the forces acting upon the wire, with a view to clearly setting forth in what manner and to what extent these forces limit the elevation attainable with a given kite.

If we could employ a wire having no weight, and so fine that the pressure of the wind upon it would be wholly inappreciable, then, as more and more of this wire is paid out to it, the kite would pass outward and upward along the same straight line, such as $R\ K$, Fig. 72, retaining always the same angular elevation as seen from the reel. Provided the wind continued unchanged in force, there would be no limit to the height to which a kite could be flown under such circumstances. Unfortunately, however, we can not fly kites with wire having no weight and against which the wind will not press, and, in consequence, our actual kite behaves in a very different manner from that described above. Supposing, as before, that the wind force is the same at all points, high or low, the results we will actually obtain with the kite above employed will be something like these: When but a short length of wire is paid out to the kite, it will take its position upon the same line, $R\,K$, as before; that is, for example, at K_1. When more wire is unreeled, the kite does not continue upward on this line, but, instead, drifts gradually away to leeward and assumes, successively, such positions as at K_2, K_3, K_4, etc., which positions lie on a curve identical with that of the line, but having the ends and sags reversed. An important feature, common to all of the positions the kite may assume, is that *the portion of the wire next the kite*

remains always at exactly the same inclination. The inclination is not only the same for all positions, but is the same as it originally was at $R K_1$. Changes of the wind force and other influences may cause this inclination of the wire to change, but the mere reeling out or in of the wire itself has no effect on the inclination. With a certain amount of wire out, the portion next the reel becomes horizontal, and the limit of altitude is then reached. The kite can lift no more line. All these effects have been brought about under the limitations imposed by the action of gravity and the wind upon the wire. We have mentioned the wind equally with gravity as affecting the wire. It is probable that with moderate wind forces the pressure upon wire, owing to its fineness in proportion to its weight and strength, is a smaller and less important force than gravity.

By the aid of well-known mathematical formulæ we can determine in the most complete and exact manner all the effects due to the action of gravity on the wire. On the other hand, the effects of the combined action of wind and gravity are of a very complex character, are but little known and understood, and can be mathematically represented only in a most general and imperfect manner. The effect of the wind pressure on the wire will be disregarded for the present and we will proceed to develop the properties of the curve assumed by the kite wire as if it were wholly dependent upon gravity alone. We will indicate afterwards how certain allowances can be made for the wind effect.

PROPERTIES OF THE CATENARY.

The name catenary is applied by mathematicians to the curve assumed by a chain or perfectly flexible inextensible string of uniform weight, when suspended from two points and acted upon by gravity alone. The kite wire is far from being perfectly flexible, but when the curve it assumes is formed on a large radius, as in kite flying, the wire may be regarded as perfectly flexible and the curve a true catenary, except for the wind effects. We may conceive that, owing to the stiffness and springiness of the wire, the curve in its minutest details acquires very small, but relatively long, waves and sinuosities. These, however, are utterly inappreciable and of no importance when steel wire is used. In the case of strings, the wind effect is more important, and, moreover, the extensible properties of the string prevent the actual curve from being a true catenary. We make mention of these disturbing influences, but do not attempt to give them further consideration.

The catenary possesses many very remarkable and interesting properties that have a more or less important bearing upon the art of flying kites. In presenting and treating of these properties we can scarcely avoid the use of certain equations, but we hope the verbal statements of results and conclusions reached by their aid will be interesting to both mathematical and non-mathematical readers alike.

The fundamental equations of the catenary may be written in a variety of forms, depending upon the variables employed. Each equation expresses some interesting property of the curve. Some of the forms most convenient for use are the following:

$$y = \sqrt{s^2 + c^2} - c \tag{1}$$

$$s^2 = y^2 + 2\,y\,c \tag{2}$$

$$x = c \text{ nap. log. } \frac{s + \sqrt{s^2 + c^2}}{c} \tag{3}$$

$$\tan.\,\theta = \frac{s}{c} = \frac{d\,y}{d\,x} \tag{4}$$

$$t = w\,(c + y) \tag{5}$$

In these equations the origin of coordinates is taken at the point where the curve is horizontal; s is the length of the curve measured from the origin, c is a constant, θ is the angle of inclination of the curve with the horizontal at the upper end of a portion of length s, t is the tension at this upper end, and w is the weight per unit length of the material of which the catenary is formed.

In Fig. 73 let $A\ O\ B$ represent a catenary. The curve has similar branches on either side of $O\ Y$, but we are generally concerned with only a portion of the curve on one side. If the wire is just horizontal at the reel, then the position of the reel will be represented by the point O in the diagram. If the wire at the reel is inclined upward, more or less, then the position of the reel will be represented on the diagram by some such point as R, at which point the curve is inclined at the same angle as the wire at the reel.

Tension.—The tension of the wire at the lowest point, that is at O, when the curve is horizontal is less than at any other point. The quantity c in the equation above is given by the expression $c = \frac{t_0}{w}$. That is, c is the length of a piece of wire whose weight equals t_0, the tension in the curve at the lowest point. Extend the line $Y\ O$ down to O', making $O\ O' = c$, and draw the horizontal line $D\ D'$. This line is known as the *directrix* of the catenary. We found above that c was the length of a piece of wire whose weight equaled the tension at the lowest point. Any other vertical line, such as c', drawn from a point p on the catenary to the directrix represents, in like manner, the tension at the point p.

If $t\ \theta$ and $t'\ \theta'$ are, respectively, the tensions and inclinations of the curve at any two points, then, from equations (1), (4), and (5), there results,

$$\frac{t}{t'} = \frac{\cos.\,\theta'}{\cos.\,\theta} \tag{6}$$

Maximum height.—Let P represent the point at which the kite acts on the wire, and suppose that the reel is at O, the kite will then be at its maximum height, which is represented by the ordinate y. The whole catenary is sustained by the pull of the kite. This pull is exerted in a certain direction, and with a certain intensity. It was pointed out above that with a steady, constant wind force, and the same kite, the direction and intensity of the pull remains fixed and invariable. Let the inclination of the wire next the kite be represented by the angle θ, as indicated in Fig. 73; then, as seen from the reel, the kite will have the angular elevation $P\,O\,X = \Phi$. If s is the length of the wire up to the kite then the height of the kite will be, from equation (1),

$$h = y = \sqrt{s^2 + c^2} - c$$

Replacing c in this equation by its value in terms of tan. θ, and reducing, we obtain

$$h = y = \frac{s}{\sin.\theta}(1 - \cos.\theta) \qquad (7)$$

This equation tells us that when a kite has taken up all the line it can carry the height may be expressed in terms of the length of the line and the inclination of its topmost portion. If we imagine several kites in the air, some small ones restrained with fine threads and strings, others larger with fine wires, others again still larger with heavy cables, and if we suppose further that all these kites pull their respective lines at the same angle θ, and that when the same length of line is out the bottom end is just horizontal, then equation (7) tells us that all these kites will be at the same elevation and that the curves of their respective lines will be exactly alike whether the lines are light or heavy. The only difference in the conditions existing in the several lines will be one of tension, which will necessarily be greater in the heavy than in the light lines. These statements are graphically verified by a very simple experiment. Take several chains or other very flexible strings of very different weights per lineal foot, suspend exactly equal lengths of these chains and strings between any two points, the curves assumed will be identical. We learn further from equation (7) that so far as the action of gravity on the kite line is concerned nothing is to be gained or lost by the use of either light or heavy lines. The tension under given conditions will be exactly proportional to the weight of the line employed. Heavy lines will require proportionally larger kites to produce the same effects. This is evident from equation (5)

$$t = w(c + y) = w\left(\frac{s}{\tan.\theta} + h\right) \qquad (8)$$

in which for the same values of s, θ, and h the tension is directly proportional to w.

Angular elevation at maximum height.—Returning to the consideration of a single kite at P, Fig. 73, Φ is the angular elevation of the kite observed at the horizontal point of the curve and when the linear altitude of the kite is a maximum. From trigonometry we have

$$\tan. \Phi = \frac{y}{x}$$

Substituting in this equation the value of y in equation (7) and x from equation (3), eliminating c by means of equation (4), and reducing, we get

$$\tan. \Phi = \frac{y}{x} = \frac{1 - \cos. \theta}{\cos. \theta \text{ nap. log.} (\sec. \theta + \tan. \theta.)} \qquad (9)$$

The second member of this very interesting equation contains only the quantity θ. The meaning of this is that when a kite has taken out all the line it can carry, or when the line at the reel is horizontal, the kite's angular elevation will be a minimum, and will depend entirely upon the inclination of the upper part of the line next the kite. If we imagine several kites of different sizes pulling with different forces, but all pulling their respective lines at the same angle, then these kites, when each has lifted all the wire it can carry, will all have the same angular elevation measured from the lowest point of the line. If these lowest points are all brought together at a common point represented, for example, at O, in Fig. 73, the kites will all take up positions one behind the other as at P, P', P'', etc., on the straight line, $O\ P$.

Isoclinals.—It results from the above that if we draw a large series of catenaries, each corresponding to a given value of c, upon the same coordinate axes as in Fig. 74, then a line like $O\ C$, radiating from the origin O, will intersect every conceivable catenary at the same angle, and the tangents to the curves at the points of intersection will form a system of parallel lines. Any other radial line, as $O\ C'$, will intersect at a new angle and form a different set of parallel tangents. The radial lines under these circumstances may be called isoclinals, and designated C_{50}, C_{60}, etc., corresponding to the angles of inclination of the curve at the points of intersection. All conceivable catenaries formed upon the coordinate axes $O\ X$ and $O\ Y$ must, in the diagram, be comprised within the space above the axis $O\ X$ and no two of the catenaries can intersect. Fig. 75 is a diagram embracing a comprehensive system of lines, catenaries, etc., formed upon the principles stated above. These principles have important applications with respect to the behavior of kites.

The angle of inclination of that part of the wire that is next to the kite, or the bridle, tends, as we have seen, to remain comparatively constant, it changes to some small extent with changes in the force and vertical component of the wind, and the angle differs more or less in different kites. Other things

remaining the same, however, the real problem in designing kites that shall attain great elevations is to cause this angle to be as great as possible. We see now the reason for this. The position of a kite which pulls the wire at an angle of 50° to the horizontal must, for the maximum height, be represented by a point on the line $O\ C_{50}$ of Fig. 75. The corresponding angular elevation Φ, as seen from the reel and as given by equation (9), is only $\Phi = 28° 48'$, and it makes no difference what kind of line is employed or how much is paid out, the position of the kite pulling at an angle of 50° must, when it attains its maximum elevation, be represented by a point on the isoclinal C_{50}. Similarly, a kite pulling at 60° attains its maximum elevation at an apparent angular altitude of $\Phi = 37° 13'$, and in the diagram, Fig. 75, its position is represented by some point on the isoclinal C_{60}.

Isoclinals for practical cases.—Having thus, from the properties of the catenary, learned the effects resulting from pulling the upper end of a kite line in different directions, let us refer to actual observations on kites and ascertain at what angles the wire is actually pulled in practical cases. Table IX contains the results of numerous observations upon kites and the angles we now seek are given in one column under the heading θ = inclination of wire at kite. The smallest θ angle recorded is 48.8° and the largest 64.2° and it happens that both results were obtained with the same kite, namely, the three plane kite shown in Fig. 56. The difference between these two values is partly due to differences of wind force, but also to alterations made in the bridle on different occasions. Our experience with this class of kites shows that the angle between the horizontal and the wire next the kite rarely exceeds 60°, except with kites of the best form and under very favorable conditions of wind. A greater inclination than 60° may in some cases be obtained with kites of light weight by adjusting the bridle so that the angle of incidence is small. In that case, however, the wind pressure is lessened and the gain that arises from a steeper angle of pull is more than counterbalanced, perhaps, by the diminution in the amount of the pull. The selection of the most advantagous angle of incidence is an interesting point which will be considered later.

Equitensals.—Referring again to Fig. 75 we recall that we found that, when at their maximum height, the positions of all kites pulling at 50° may be represented by points on the isoclinal C_{50}, similarly those of kites pulling at 60° by points upon the isoclinal C_{60}. Now, suppose it were possible to cause a kite to continue to pull with the same constant force, while the direction of the pull at the kite is changed, it will be interesting to inquire what effect a change in the angle of pull can produce upon the maximum possible elevation of a kite. From a mathematical standpoint the answer to this question consists in drawing a line in Fig. 75 of such a character that the tensions on all the catenaries at the points of intersection with the new line will be the same. Such in-

tersecting lines may be called equitensals, since they cut the catenaries at points of equal teneseness or pull on the line. We may find the equation of such a line as follows: From equation (8) we have for the tension at a point whose elevation is h and where the curve is inclined at an angle θ,

$$t = w\left(\frac{s}{\tan.\theta} + h\right)$$

from which

$$\frac{s}{\sin.\theta} = \frac{t - h\,w}{w\cos.\theta}$$

Substituting this expression in equation (7) and solving for h we have

$$h = \frac{t\,(1 - \cos.\theta)}{w} \qquad (10)$$

which is the equation sought. This equation may be stated in another form, in terms of s, by deriving it in a similar manner from equations (7) and (8) by eliminating h. The result is

$$s = \frac{t}{w}\sin.\theta \qquad (11)$$

Equation (10) gives us the maximum height attainable by a given kite pulling at an angle θ with tension t, the wire weighing w pounds per unit length. Equation (11) gives the length of wire required by the kite to attain this position.

In Fig. 75 $T\,T'$ is an equitensal passing through the point P. The points at which this line crosses the isoclinals C_{50}, C_{60}, C_{65}, etc., are the positions that would be taken by kites that are at their maximum altitudes and all pulling equally hard, but at angles of 50°, 60°, and 65° respectively. In constructing any equitensal, such as $T\,T'$, we observe that if h_{50} equals the height at which the equitensal crosses the isoclinal of 50°, then the height at which it crosses the isoclinal of 60° will be

$$h_{60} = h_{50}\,\frac{1 - \cos.\,60^\circ}{1 - \cos.\,50^\circ} = 1.400 h_{50}$$

Drawing a horizontal line on the diagram at a height $= 1.4h_{50}$ above the line $O\,X$, the point at which it intersects the isoclinal C_{60} is a point on the desired equitensal. Other points may be located in a similar manner.

Furthermore, equation (11) shows that if s_{50} is the maximum length of the curved line of wire that a kite pulling with a certain force can sustain when the angle of pull at the kite is 50°, then by pulling with the same force at an angle of 60°, it will carry up a length of wire given by the expression

$$s_{60} = s_{50}\,\frac{\sin.\,60^\circ}{\sin.\,50^\circ} = 1.130 s_{50}$$

These results may be presented in another and perhaps more striking manner. Suppose a kite pulling with a certain force at an angle of 50° is able to attain a maximum elevation of 1,000 feet. If now, by any means, we can cause the kite to pull with the same force at an angle of 60° instead, it will attain an elevation of 1,400 feet, being a direct gain of 400 feet in 1,000 for an increase of 10° in the angle. The length of wire required in the first case will be 2,145 feet, and in the second case 2,425 feet. Although 400 feet have been gained in elevation by the change, yet only 280 feet more of wire have been required. With the kind of wire employed in the Weather Bureau work, weighing 2.155 pounds per 1,000 feet, the tension required at the kite in both cases will be 6.03 pounds. The weight of the additional 280 feet of wire is 0.603 pounds. The kite then, without pulling any harder, flies 400 feet higher and carries 0.603 pounds more wire. This gain in height and carrying power is wholly due to the improvement in the angle of pull in the kite. It is important to notice here that this increase in the angle of pull must not be brought about, as it might be, by lessening the angle of incidence of the kite, because in that case the pull of the kite would also be lessened, and our comparison has been drawn on the supposition that the pull has remained constant. There is a way, however, in practical cases by which the desired improvement in the *direction* of the pull can be brought about without sensibly diminishing the *intensity* of the pull. If the kite pulling at 50° is badly defective in respect to edge pressures, waviness and fluttering, eddy effects, etc., then by eliminating these defects the angle of pull will be increased with only a very a very slight diminution of pull. From actual measurements upon Weather Bureau kites, gains of as much as 10° in the angle of pull are sometimes possible in practical cases with no loss in intensity of pull.

Incidence for maximum altitude.—We have noticed before that the advantage which may be gained by lessening the angle of incidence of the kite, and which, other things remaining the same, would tend to make the direction of pull steeper, may be more than counterbalanced by the diminution in the intensity of the pull, which necessarily accompanies a diminution of the angle of incidence. Furthermore, there is another wholly independent and very important factor bearing directly upon this question, namely, the efficiency as affected by changes in the pressure of the wind. It was shown on page 77 that when the wind pressures upon kites became relatively small, as may be the case with relatively small angles of incidence, the efficiency angle, owing to the pronounced effect of the weight of the kite, also became small. We may state this in other words, as follows: Lessening the angle of incidence not only always lessens the pull but it may also lessen the angle at which the kite pulls the string, owing to the detrimental effect of the weight of the kite under feeble wind forces. If we set the kite at too great

an angle of incidence it will fail to reach a great elevation, because in spite of the strong pull it may exert, the direction of this pull is at too unfavorable an angle for the best effect. On the other hand, too small an angle of incidence, owing to the falling off in efficiency, likewise fails to bring about the most satisfactory result. It is apparent, however, that between these extremes is a condition, a particular angle of incidence, leading to the maximum linear elevation. On account of the change which may take place in the efficient action of the kite when the incidence of the kite is changed, and arising more particularly in light winds it is probable that the *incidence for maximum effect* should be determined independently and separately for each kite. Data is not available by which this can be done at present, and it will be quite as instructive, in the present case, to analyze the problem in a general way. This will give an idea as to the approximately best angle of incidence.

Ideal and actual kite.—There are two conditions for which we may seek the solution of this problem. We may consider only the special case of the ideal kite, with a constant efficiency of 100 per cent, or we may ascertain the best incidence of actual kites of several stated efficiencies. The complete solution would require that we suppose the efficiency to vary as a function of the incidence. It is in respect to this condition that data is as yet wanting. We will, therefore, first solve the equations for the ideal conditions, and afterward consider the actual kite, with several different efficiencies, in order to give a range between which most practical cases will fall.

Best incidence—ideal case.—If i is the angle of incidence of the kite, then, in the ideal case, the direction of pull will be,

$$\theta = (90^\circ - i).$$

Now, the force with which the wind presses upon flat surfaces at different angles of incidence is given with a close degree of approximation by Duchemin's formula, as follows:

$$P = P_0 \frac{2 \sin. i}{1 + \sin.^2 i} \tag{12}$$

In this expression P represents the proportional pressure upon the inclined surfaces of the kite and P_0 the corresponding pressure of the wind upon the same surfaces exposed normally to the wind direction. The formula is strictly applicable to flat surfaces only. It is applied to kites in the manner that follows because a better formula is not known. We desire to know, at least approximately, which is the best angle of incidence in a given case, and this we believe Duchemin's formula will give.

The pull of an actual kite—that is, the tension in the wire at its upper end—is represented by the diagonal of a parallelogram, of which P from the above equation is one side and W, the weight of the kite, is the adjacent side. The included

angle is $180° - i$. In the ideal kite we assume that the weight is inappreciable, compared with the wind force on the kite, and, as a direct consequence of this assumption, the diagonal of the above mentioned parallelogram coincides with the side P; in other words, in the ideal kite the pull is equal to the pressure of the wind; hence we may write for the tension in the wire at the upper end,

$$t = P = P_0 \frac{2 \sin. i}{1 + \sin.^2 i}$$

From this equation and (10), first replacing θ in the latter by its value, $\theta = (90° - i)$, we have:

$$h = \frac{2P_0}{w} \frac{\sin. i - \sin.^2 i}{1 + \sin.^2 i} \qquad (13)$$

This equation gives in terms of the angle of incidence the height attainable by a given ideal flat kite when it has taken out all the line it can sustain. To find the incidence which will give the maximum possible elevation, we need only to determine the value of i from the differential coefficient of equation (13) when that coefficient is placed equal to zero. That is,

$$\frac{dh}{di} = \frac{2P_0 \cos. i}{w(1 + \sin.^2 i)^2} \left[1 - \sin.^2 i - 2 \sin. i \right] = 0 \qquad (14)$$

whence

$$\sin.^2 i + 2 \sin. i = 1. \qquad (15)$$

That is,

$$\sin. i = \pm \sqrt{2} - 1 = + 0.4142 \text{ or } - 2.4142$$

and

$$i = 24° \, 28'.$$

The angle of incidence with which the ideal flat surface kite can attain the highest elevation is therefore 24° 28′, and the corresponding inclination of the wire at the kite is 65° 32′. The angular elevation of the kite from the reel when the wire is horizontal will be, from equation (9), $\Phi = 42° \, 47'$.

Best incidence for actual kite.—In the case of the actual kite the efficiency will necessarily always be less than 100 per cent, which is practically equivalent to saying that in the actual kite the angle between the wire and the kite will always be less than 90°. This angle of the string is affected by: (1) the wind pressure upon the edges of the kite, waviness, fluttering, eddies, etc., which deflect the action line of the total wind pressure upon the kite away from normal, (2) the weight of the kite must be overcome, and to do this the direction of *pull* must be deflected away from the direction of the *wind pressure*. Both these effects (1) and (2) act in the same manner; that is, if g represents the angular deflection due to gravity or the weight of the kite, and e that due to edge pressures, then the direction of pull will be deflected away from the normal to the kite surfaces by an angular amount, represented by

$(e+g)$. The relations of the angles in question are shown in Fig. 76. If P represents the pressure of the wind normal to the kite surfaces, then the total wind pressures $O\,Q$ will be $P'=P$ sec. e. Furthermore, in the triangle of forces $O\,Q\,R$, from trigonometry, the side $O\,R$ = pull of kite, will be given by the expression,

$$t=\sqrt{P^2 \sec.^2 e + W^2 - 2\,P\,W \sec. e \cos. (i+e)} \qquad (16)$$

The angle e is not a known quantity; it is a small angle which is, it seems, practically constant in a given kite, but may possibly vary with the wind force. This angle, in certain kites has been determined by means of the diagram of forces which is described on page 84. The angle in the best cellular kites has been found to be under 3°, whereas with inferior kites the value has slightly exceeded 10°. The term sec. e is, therefore, on account of the small value of e, a quantity which we may assume to be constant without introducing any important error.

In regard to the term cos. $(i+e)$ it may be said that i, the best incidence for the actual kite must necessarily be smaller than that for the ideal flat surface kite, which we have found to be 24° 28′. The reason for this is that the effects due to edge pressures, waviness, eddies, etc., tend to depress the kite by forcing it to leeward away from the zenith. To offset this it is necessary to set the kite at a smaller incidence which tends to make it approach the zenith point. We may therefore expect to find the best incidence for the actual kite with flat surfaces smaller than 24°. Since e, as we have seen for the better class of cellular kites observed, is less than 3°, we may assume that $i+e$ will not exceed 25° in actual kites. Moreover the term can not change its value more than a few degrees in extreme cases, which fact together with the general unimportance of the term in any case renders refinement unnecessary and we will therefore assume that this term has the constant value,

$$\cos. (i+e) = a$$

In work with actual kites we can not profitably attain high elevations unless the wind force upon the kite is considerably greater than the weight of the kite. Under ordinarily favorable condition the wind force P will be from 5 to 7 times the weight of the kite and will frequently be still greater. As we seek more particularly to discover the best incidence under conditions of favorable winds we will assume that the weight of the kite in equation (16) is expressed in terms of P, thus, $W=b\,P$, in which b is a small fraction rarely as great as 0.2 and often less than 0.1.

According to the several assumptions we have made above equation (16) becomes,

$$\text{Pull} = t = P\sqrt{1+b^2-2\,a\,b} = k\,P$$

and adopting Duchemin's formula, equation (12), as applicable to cellular kites with flat surfaces, we get,

$$t = k\,P = k\,P_0 \frac{2\,\text{sin.}\,i}{1 + \text{sin.}^2\,i} \tag{17}$$

In reducing the expression (16) to this form we virtually assume that the tension on the wire next the kite does not undergo any variations with changes of incidence except such as are wholly due to changes in the wind force. This is not strictly the case, for there is a slight variation due to the effects of the weight of the kite and these are fully included in (16). The amount of these variations, however, in the extreme cases will barely attain to 1% of the pressure itself, and we believe that by neglecting them, as we shall do, no serious error will result in the values deduced for the best angle of incidence.

From Fig. 76 we see that

$$\theta = 90° - (e + g) - i.$$

$90° - (e + g)$, it will be noted, is the angle of inclination of the wire to the kite and is a known angle when the efficiency of the kite is known. We have heretofore called this angle the efficiency angle (page 72). Knowing the percentage efficiency, E, of a kite, the efficiency angle, D, is given by the relation,

$$D = 90 \times E$$

and for the inclination of the wire at the kite we may write

$$\theta = D - i$$

with the values of t and θ, given above, and equation (10), we obtain the following equation for the maximum elevation that can be attained by actual flat surface kites depending upon the pull and the angle of incidence; (13) is the corresponding equation for ideal kites,

$$h = \frac{2\,k\,P_0\,(\text{sin.}\,i - A\,\text{cos.}\,i\,\text{sin.}\,i - B\,\text{sin.}^2\,i)}{w \qquad (1 + \text{sin.}^2\,i)} \tag{18}$$

In this equation $A = \text{cos.}\,D$ and $B = \text{sin.}\,D$ are sensibly constant for any given kite under conditions of wind force favorable for gaining high elevations.

When the efficiency is 100% $D = 90°$ and $k = 1$. Equation (18) then reduces to (13) for the ideal kite as should be the case.

Differentiating (18) and reducing, we have,

$$\frac{dh}{di} = \frac{2\,k\,P_0}{w\,(1 + \text{sin.}^2\,i)^2} \left[\begin{array}{c} (\text{cos.}\,i - A)\,\text{cos.}^2\,i \\ + 2\,\text{sin.}\,i\,(A\,\text{sin.}\,i - B\,\text{cos.}\,i) \end{array} \right] \tag{19}$$

which is quite analogous to the similar equation (14) for ideal kites. Placing the second member equal to zero for a

maximum, we obtain a form convenient for computation, as follows:

$$\cos. i = A \left[1 - 2 \left(\tan.^2 i - \frac{B}{A} \tan. i \right) \right] \qquad (20)$$

B and A, it will be remembered, depend upon the efficiency. When this is 100 per cent, equation (20) reduces to,

$$\sin. i = \pm \sqrt{2} - 1,$$

the same as already found for the ideal kite.

By means of equation (20) the best angle of incidence for kites of several different degrees of efficiency, ranging from 70 to 95 per cent, have been computed by methods of approximation, and are given in Table XI, with other useful information. Efficiencies as low as 70 per cent ought not to obtain with good kites, except, perhaps, in very light winds, in which case ascensions to considerable elevations with such kites are not practicable. On the other hand, an efficiency of 95 per cent is not by any means unattainable when the wind velocity is favorable—that is, 15 miles per hour or more.

TABLE XI.—*Best angles of incidence for flat-surface kites.*

	Efficiency.						
	70%	75%	80%	85%	90%	95%	100%
Efficiency angle..D	63° 00′	67° 30′	72° 00′	76° 30′	81° 00′	85° 30′	90° 00′
Best incidence....i	18° 30′	19° 33′	20° 36′	21° 36′	22° 34′	23° 31′	24° 28′
Inclination.......Θ	44° 30′	47° 57′	51° 24′	54° 54′	58° 26′	61° 59′	65° 32′
Elevation.........Φ	24° 49′	27° 17′	29° 53′	32° 42′	35° 46′	39° 07′	42° 47′
Altitude, feet ....h	1,000	1,202	1,424	1,666	1,928	2,207	2,504
Pull, pounds ......t	7.5	7.8	8.2	8.4	8.7	9.0	9.2
Length of wire....s	2,444	2,703	2,959	3,207	3,447	3,674	3,890
Ratio..........$h \div s$	0.410	0.444	0.481	0.518	0.559	0.602	0.645

In addition to the best angles of incidence for actual kites of several efficiencies, Table XI gives the maximum heights attainable, computed from equation (18), upon a uniform basis of such conditions as would be required by the kite of 70 per cent efficiency to attain an elevation of 1,000 feet; that is, if the efficiency of this same kite could be increased from 70 per cent to 90 per cent, for example, and with no change whatever in its surface, weight, or other features, it would then, with exactly the same wind, be capable of attaining nearly double the altitude, namely, 1,928 feet. The constant required in equation (18) for these computations is obtained by making $h = 1{,}000$ when $i = 18° 30'$, and solving for $2\,k\,P_0 \div w = 12{,}090$. The assumption that k is constant, as explained above, will not affect the results to an important extent. The pull, t, at the kite and the length of wire, s, may be found most easily from equations (10) and (11), respectively, in which w is the weight per foot of the steel wire employed at the Weather Bureau, viz, 0.002155 pounds.

A kite showing an efficiency of 85 per cent will, in most cases, be regarded as a very good kite, although still higher

efficiencies up to 95 per cent are probably attainable. The altitude attained by an 85 per cent kite is less than that of the 95 per cent kite by 541 feet on a moderate elevation of 1,666 feet. For an ascension of 1 mile the 85 per cent kite would be deficient by over 1,700 feet, that is, the 95 per cent kite under precisely the same circumstances would ascend 1,700 feet more than the mile.

It is plain that where such large gains as this are possible, it devolves upon every one who aims to get the highest elevations to fully inform himself as to the real merit of his kites and see to it that they are bridled and flown under the best adjustments.

The results which have been brought out in the foregoing discussions concerning the best incidence depend upon Duchemin's law of variations of pressure with incidence, and apply only to kites with flat as distinguished from arched surfaces. The best incidence for arched surfaces is undoubtedly smaller than for flat surfaces. We have also disregarded the effect of the wind upon the wire, which while small, is still of some importance, and as its effect is to drift the kite to a position further away from the zenith than would otherwise be attained, the best incidence when the wind effect is included will be smaller than given in Table XI.

Maximum sag and slack of wire.—We have called the angles between the curve and its chord the sag of the wire, as for example the angles S and S', Fig. 67. We will similarly use the term *slack* to designate the difference between the length of the chord and the length of the curve itself.

When the wire is horizontal at the reel the angle of sag at that point is then the same as the angular elevation of the kite, that is $S' = \Phi$, the sag at the kite is similarly, $S = \theta - \Phi$. Dealing with portions of the catenary on one side only of the Y axis, S' is the maximum sag possible.

If r is the air-line distance between the reel and the kite when the wire is horizontal, then,

$$r = \frac{h}{\sin.\ \Phi}$$

combining this equation with (7) we get,

$$r = \frac{s\,(1 - \cos.\ \theta)}{\sin.\ \theta\ \sin.\ \Phi}$$

and the slack will be,

$$s - r = s\left(1 - \frac{1 - \cos.\ \theta}{\sin.\ \theta\ \sin.\ \Phi}\right)$$

We will consider hereafter the sag and slack for conditions less than the maximum.

Partial ascensions.—In the discussion of the properties of the catenary we have thus far treated only of the behavior of kites when they have ascended to their utmost limit and sustain all the wire they can carry. All those conditions which

tend to produce the best results when the wire is horizontal at the reel are equally beneficial in the case of partial ascensions where the kite carries up only part of the wire it can sustain, and the portion at the reel is inclined to the horizontal at a slight angle. Partial ascensions are the usual cases in practice. When the wire at the reel becomes horizontal the frequent diminutions of wind force allow it to temporarily sag to the ground or to interfere with trees, buildings, etc., and in general, therefore, we must provide some margin within which the usual variations of pull may occur without permitting the wire to sag to an objectionable extent. Furthermore we see from Fig. 72 that, since the path described by the kite in attaining its maximum elevation is the inverted catenary, the last portion of the ascent is very slight, and but little is gained in paying out wire to the last extremity.

The constancy of the inclination of the upper portion of the wire in the successive positions assumed by a kite passing upward from the reel to a maximum elevation, as shown in Fig. 72, was pointed out on page 91. The several curves of the wire are all portions of one and the same catenary, that is, portions of the curve $R\ K_3$. When but a short length of wire is out, its curve is the portion of the catenary from K_3 down to such a point as R_1. With greater and greater lengths of wire out it is as if the reel were moved backward and downward along the catenary passing through positions such as $R_2\ R_3$, etc., while the kite has remained stationary. When we know the angle of inclination of the wire at the reel in a given case we can locate its position on the catenary. The diagram in Fig. 75 represents all conceivable catenaries and may therefore be employed to represent graphically any partial ascension. For example, if the wire at the reel is inclined at an angle, $\theta' = 10^0$, then the position of the reel is represented in the diagram by some point on the isoclinal C_{10}. The particular point on the isoclinal will depend upon the tension, t', at the reel. If this is known, then the position of the reel is located at the point of intersection of the isoclinal C_{10} and the equitensal t'. The catenary passing through the point of intersection is the particular one representing the kite wire in the given case and the position of the kite at the upper end may be located in several ways.

If θ, the inclination of the wire at the kite is, for example, $\theta = 60°$, then the position of the kite will be represented by the point of intersection of the particular catenary already found with the isoclinal C_{50}. If Φ' is the angular elevation of the kite from the reel we may lay off on the diagram a line making the angle Φ' with $O\ X$ and passing through the point representing the position of the reel. The upper intersection of this line, with the particular catenary representing the kite line, gives the position of the kite. There is still another and more general graphical way of locating the kite on the diagram. It is possible to draw a system of lines on the diagram resembling the equitensals and crossing the cate-

naries, but cutting off *equal arcs* of the curves measured from the origin. The equation for these *equiarcals* is obtained simply by making θ and h the variables in equation (7) thus:

$$h = \frac{s}{\sin.\theta}(1 - \cos.\theta)$$

Lines of this character are designated on the diagram by the letters L_1, L_2, etc. The subscripts indicate the length of arc cut off from the origin in units of 1,000 feet. Having located on the diagram the position of the reel, in the case of a partial ascension, the equiarcal passing through that point gives the length on the catenary from the reel to the origin. Knowing, in addition to this, the length of wire out, the sum of the two determines the equiarcal for the kite. The point of intersection of this with the particular catenary passing through the reel gives the desired position of the kite.

The linear elevation of the kite is the vertical distance on the scale of the diagram between the positions found for the reel and the kite.

By such methods as we have thus described a diagram of the kind shown in Fig. 75 may be employed as a graphic chart completely representative of any ascension that may be made with a single kite. Numerical tables for deducing elevations, etc., will probably be preferable in many cases but the chart shows the results graphically and has been discussed at length more particularly because of the several interesting properties of the catenary involved in its use.

General equations for partial ascensions.—Fig. 77 represents a partial ascension in which the reel is at R and the kite at K, with the origin of coordinates at O. Letters designating the coordinates of the catenary at the point representing the reel are distinguished by a superscript, ($'$). The linear elevation of the kite is $h = y - y'$ and the length of wire out is $l = s - s'$.

If t' is the tension of the wire at the reel then from equation (10) we have,

$$y' = \frac{t'}{w}(1 - \cos.\theta')$$

Eliminating c from equation (1) by its value in terms of t' and θ' and replacing s by its value $s = l + \frac{t'}{w}\sin.\theta'$ we obtain,

$$y = \sqrt{l^2 + \frac{2\,l\,t'}{w}\sin.\theta' + \left(\frac{t'}{w}\right)^2} - \frac{t'}{w}\cos.\theta' \qquad (21)$$

Whence,

$$h = y - y' = \sqrt{l^2 + \frac{2\,l\,t'}{w}\sin.\theta' + \left(\frac{t'}{w}\right)^2} - \frac{t'}{w} = r\sin.\Phi' \qquad (22)$$

From this equation we learn that when the length of wire

out is known together with the tension and inclination at the reel, the height of the kite is given, even though it is concealed from view, as by clouds, darkness, its remote distance, etc. This results from a general property of the catenary and the equation is equally applicable to the case of either partial or complete ascensions. Owing to great momentary variations that take place in the tension of the wire, calculations of elevations depending upon the tension at the reel will not, as a rule, be as accurate as those deduced by other methods, but equation (22) will undoubtedly prove useful in cases where other methods of ascertaining elevation are not available.

In passing, it may be remarked that the elevation of an invisible kite deduced by equation (22) will be more accurate, as the sag in the wire is greater.

If θ and t are the inclination and tension of the wire at the kite, we may write,

$$y = \frac{t}{w}(1 - \cos.\theta), \text{ and } y' = \frac{t'}{w}(1 - \cos.\theta')$$

whence, by equation (6), we get,

$$h = y - y' = \frac{t}{w}\left(1 - \frac{\cos.\theta}{\cos.\theta'}\right) = r \sin.\Phi' \qquad (23)$$

an equation which we shall have occasion to use hereafter.

Observed angular elevation.—Instead of measuring the tension in the wire at the reel in a given case, we may observe the angular elevation, Φ', of the kite from the reel, and if we can determine the relation between Φ' and t', the latter may be eliminated from equation (22). From trigonometry we have

$$\tan.\Phi' = \frac{h}{x - x'}$$

The value of x' in terms of t' and θ', deduced from equations (3), (4), and (11), is,

$$x' = \frac{t'}{w}\cos.\theta' \text{ nap. log. } (\sec.\theta' + \tan.\theta') \qquad (24)$$

Similarly the value of x is,

$$x = \frac{t'}{w}\cos.\theta' \text{ nap. log. } \frac{l + \frac{t'}{w}\sin.\theta' + \sqrt{l^2 + \frac{2lt'}{w}\sin.\theta' + \frac{t'^2}{w^2}}}{\frac{t'}{w}\cos.\theta'}$$

From these values of x and x' and the value of h given in (22), we obtain a very complex transcendental equation, representing the relation between the angular elevation at the reel and other quantities that are known. The value of t' corresponding to a given value of Φ' can be deduced from this equation only by methods of approximation. It will not, therefore, be practicable to eliminate t' from equation

(22) in the manner contemplated, but we can, by tabulating a limited number of values of the several quantities, deduce the percentage of slack in the wire corresponding to such conditions as are likely to occur in practice, and thus provide a method for accurately computing the height of kites, in partial ascensions, that does not depend upon the tension of the wire.

Slack in the wire in partial ascensions.—Let r be the length of the chord of the catenary from the reel to the kite, then,

$$r = \frac{h}{\sin. \Phi'} \tag{25}$$

$$\text{slack} = l - r \text{ and percentage of slack} = 1 - \frac{r}{l}$$

The ratio of any chord of a catenary to the corresponding arc is given by the equation

$$\frac{r}{l} = \frac{\cos. \theta' - \cos. \theta}{\sin. \Phi' \sin. (\theta - \theta')} \tag{26}$$

which may be obtained from equation (23) by eliminating $\frac{t}{w}$ in terms of l.

The relation between Φ', θ, and θ' is obtained by forming an equation for x similar to (24) for x', whence, with the value of h in (23), there results,

$$\tan. \Phi' = \frac{h}{x - x'} = \frac{\sec. \theta - \sec. \theta'}{\text{nap. log.} \left[\dfrac{\sec. \theta + \tan. \theta}{\sec. \theta' + \tan. \theta'} \right]} \tag{27}$$

Table XII contains a series of values of Φ' deduced from equation (27) corresponding to such assumed values of θ and θ' as may occur in practice. With each value of Φ' is also tabulated the corresponding percentage of slack computed by means of equation (26). The results are rigorous representations of the properties of the catenary, and even though the wind effect has been omitted, the relations of the quantities concerned are such that the wind effect on the wire can not modify the percentage of slack, corresponding to given values of Φ' and θ', except by a quantity of secondary magnitude.

TABLE XII.—*Angular elevation and percentages of slack.*

		Θ'=Inclination of wire at reel.						
		0°.	10°.	20°.	30°.	40°.	50°.	60°.
$\Theta=50°$	Slack, %	3.22	2.03	1.11	0.51	0.13	......	......
	Φ'	28.8°	32.9°	36.9°	41.0°	45.3°	......	......
$\Theta=55°$	Slack, %	3.87	2.55	1.53	0.78	0.29	0.03	......
	Φ'	32.8°	36.6°	40.4°	44.2°	48.2°	52.6°	......
$\Theta=60°$	Slack, %	4.53	3.10	1.97	1.11	0.50	0.13	......
	Φ'	37.2°	40.8°	44.8°	47.8°	51.4°	55.4°	......
$\Theta=65°$	Slack, %	5.17	3.65	2.43	1.48	0.76	0.28	0.03
	Φ'	42.2°	45.4°	48.5°	51.7°	55.0°	58.5°	62.6°

TABLE XIII.—*Ratio of sag* $= S \div S'$.

	$S'=\Phi'-\theta'$=sag at reel.							
	2°	4°	6°	8°	10°	12°	14°	20°
$\theta=50°$	0.950	0.910	0.878	0.852	0.828	0.810	0.793	0.758
$\theta=55°$	0.942	0.894	0.856	0.826	0.800	0.779	0.760	0.718
$\theta=60°$	0.929	0.876	0.834	0.800	0.770	0.746	0.724	0.671
$\theta=65°$	0.918	0.854	0.804	0.766	0.731	0.705	0.681	0.627

The practical use made of Table XII is as follows: With Φ' and l we compute the approximate elevation of the kite from the equation, $h' = l \sin. \Phi'$; with Φ' and θ' we take from Table XII the corresponding percentage of slack; deducting from h' this same percentage of itself there results the actual elevation.

The ratios of the angles of sag, given in Table XIII, will be understood from what follows:

Angles of sag in partial ascensions.—In making efficiency tests we measure the angle of sag, S', at the reel, and desire to know the corresponding sag, S, at the kite. The ratio $S \div S'$ of these angles is nearly constant when S' is small, and it varies but little with different values of θ'. In computing these ratios we have used the relations $S' = \Phi' - \theta'$ and $S = \theta - \Phi'$, which are apparent from Fig. 77, and the values of Φ' deduced from equation (27).

Altitude as dependent upon pull.—Kites of different size pull with different forces. The maximum altitude a kite pulling with a given force t, at an inclination θ can attain is given by equation (10) thus,

$$h = t\,\frac{(1 - \cos. \theta)}{w} \qquad (10)$$

A kite that pulls twice as hard as another can, we see, attain twice the altitude. Moreover equation (7) shows that exactly twice the length of wire will be required. If instead of one large kite two smaller ones, each pulling half as hard but at the same angle, were made to pull, without interference, at the end of the line, it is plain that the combined action of the two kites would necessarily be equivalent to that of the large one in every respect. Suppose, however, the two kites were formed into a tandem in the usual fashion; we wish to know whether the top kite can then attain a greater, an equal, or a less elevation than that reached by the single equivalent kite.

Kites in tandem.—Some mention was made on page 21 of the greater steadiness of pull resulting from the use of two or more kites in tandem. This is an important matter in itself but does not directly concern us here as our analysis of the properties of the catenary proceeds upon the assumption that the tension on the wire is, in all cases, sufficiently steady to keep the resulting curve in a condition of complete static equilibrium. We assume further in our discussion of the dis-

tribution of kites in a tandem that all are subjected to the same wind force.

Two considerations arise in flying kites in tandem, namely, (1) having given a certain *pull*, acting in a certain direction, how shall this be employed to gain the maximum elevation? Shall the pull be concentrated and applied at the end of the kite line, or shall it be subdivided and distributed, and if so, how? (2) Having given a wire or line capable of sustaining a certain maximum safe-working tension, how shall it be employed with actual kites to attain the maximum elevation? We shall find that the same general equations will enable us to answer both these questions.

General equations for tandems.—Our equations will be sufficiently general if we assume that the different kites which go to make up the tandem are exactly equal in all respects, hence t and θ will represent the intensity and inclination of the pull of any of the kites.

Fig. 78 represents the forces acting at the point at which a second kite is attached to the line from the topmost or so-called pilot kite. Using a notation similar to that already employed, θ' and t' are, respectively, the inclination and pull of the portion of wire just above the point at which the second kite is attached. (θ' and t' result from the action of the pilot kite.) θ_2 and t_2 are respectively the inclination and pull of the portion of wire just below the point at which the second kite is attached; they represent the combined power of both kites. Constructing the parallelogram of forces between the tensions involved we obtain from trigonometrical relations,

$$t_2 = \sqrt{t^2 + t'^2 + 2\,t\,t' \cos.(\theta - \theta')} \qquad (28)$$

but,

$$t' = t\,\frac{\cos.\theta}{\cos.\theta'}$$

whence,

$$t_2 = t\sqrt{1 + \frac{\cos.^2\theta}{\cos.^2\theta'} + 2\,\frac{\cos.\theta}{\cos.\theta'}\cos.(\theta - \theta')} \qquad (29)$$

an equation which represents the resultant or combined pull of the two kites. The direction, θ_2, in which this pull is exerted, is obtained as follows: In the triangle of forces t, t', and t_2, let a be the angle included between the sides t' and t_2, then,

$$\sin.a = \frac{t}{t_2}\sin.(\theta - \theta')$$

From the diagram it is seen that,

$$\theta_2 = \theta' + a$$

In assuming that the second kite pulls at an angle θ and tension t at the point where it is attached to the main line we neglect, as we may without sensible error, the influence of the short connecting wire between the kite and main line.

The combined action of the two kites is, by the above equations, completely expressed in terms of the power of one kite. By a precisely similar process we may determine the effect of adding a third, a fourth, or any number of subordinate kites in tandem. As our object is to discover the best arrangement of kites in tandem it will suffice if we make comparisons on the basis of two kites only, since if there is a gain or a loss with two kites, a similar result will obtain with three or more.

Having attached a second kite to the line, let wire be unreeled until the portion next the reel becomes horizontal.

It seems scarcely necessary to say that under no circumstances whatever should a second kite be attached that does not pull *above* the main line and thus tend to lift it. To attach a subordinate kite that pulls *below* the main line, and therefore drags it lower, would, obviously, be absurd if we aim to attain great elevations.

The total elevation attained by the tandem of two kites is, from equations (23) and (10),

$$H_2 = \frac{t}{w}\left(1 - \frac{\cos.\theta}{\cos.\theta'}\right) + \frac{t_2}{w}\left(1 - \cos.(\theta' + a)\right)$$

This equation can be transformed into the following:

$$H_2 = \frac{t}{w}\left\{\begin{array}{l} 1 - R + \sqrt{1 + R^2 + 2R\cos.(\theta - \theta')} \\ -\cos.\theta'\Big[R + \cos.(\theta - \theta')\Big] \\ + \sin.\theta'\sin.(\theta - \theta') \end{array}\right\} \quad (30)$$

Where $R = \cos.\theta \div \cos.\theta'$.

Equation (30) expresses the maximum height that can be attained by two equal kites in terms depending upon the power of one of the kites and the point at which the second kite is attached to the main line.

The answers to questions (1) and (2), propounded above, are reached from a consideration of equations (28) and (30), as follows:

Best utilization of a given pull.—Assume that the two kites are attached side by side on the end of the main line. In this case,

$$\theta' = \theta, \text{ and } R = 1,$$

whence the height becomes,

$$H_2 = \frac{2t}{w}(1 - \cos.\theta),$$

which means that, thus arranged, the two kites attain twice the elevation of one alone, as should be the case. To show the effects of attaching the second kite lower and lower down upon the main line, we will compute the relative heights attained when the second kite is attached after the line has sagged 10°, 20°, 30°, and including the case where the second kite is not attached until the top kite has carried up all the

wire it can sustain, in which case $\theta' = 0$. We will assume that the kites pull at an angle $\theta = 55°$, and compute the elevations on the basis of the maximum height being 5,000 feet. The results are:

		Feet.	Loss. Feet.
Maximum effect, both kites at the top		$H_2 = 5{,}000$	......
Second kite attached where the sag is	$10°, \theta' = 45°$	$H_2 = 4{,}960$	40
" " " "	$20°, \theta' = 35°$	$H_2 = 4{,}850$	150
" " " "	$30°, \theta' = 25°$	$H_2 = 4{,}690$	310
" " " "	$40°, \theta' = 15°$	$H_2 = 4{,}470$	530
" " " "	$50°, \theta' = 5°$	$H_2 = 4{,}200$	800
" " " "	$55°, \theta' = 0°$	$H_2 = 4{,}040$	960

We find here that there is a continually increasing loss in the elevation attained when flying kites tandem, depending upon how much the line is permitted to sag before the second kite is attached. The best results correspond to the least sag of the wire between kites, and the maximum effect is obtained when $\theta' = \theta$; but this may mean either of two things: (1) that the kites are placed side by side at the end of the line or (2) that innumerable kites are attached along the line so close to each other that the line does not sag between them; in other words, that every particle of the line is acted upon by its kite just as it is by gravity. From the properties of the catenary thus brought out it results that the maximum service can not be obtained by flying kites in tandem. There are, however, from other considerations, many marked advantages in tandem flying, which consist in the greater steadiness of pull thereby secured under actual conditions of variable winds and greater security against accident; also the facility of using a large or small amount of sustaining surface as required by conditions of wind force. A special advantage results from the more equable distribution of the strain on the line, which otherwise, with a single kite, is a maximum at the top. In reeling in a long line of kites, it is an advantage to be able to lessen the opposing pull by the removal of one after another of the kites, rather than to have to wind them all in until the top end is reached. Notwithstanding such advantages, we must not lose sight of the marked superiority of one large kite at the end of the line when we aim to reach great elevations. Perhaps more will be gained by the use of two, to secure a more steady pull, than will be lost by virtue of the tandem arrangement, but these two kites are best placed near the top end of the line.

In connection with equation (30) it is instructive to notice the result when $\theta = 90°$. This is not attainable by kites but represents the case of captive balloons in perfectly still air, and upon the supposition that the balloons pull with a constant force at all elevations. No matter what value θ' may have between 0° and 90°, the equation shows that two balloons in tandem will go twice as high as one, etc. Furthermore, it will be found that equation (30) shows that less loss results in tandem arrangements the steeper the angle at which each kite pulls, that is, the greater the value of θ.

While equation (30) was deduced for but two kites it answers perfectly for the analysis of the effects of any number of kites, for having found the result of the combination of two kites this combination may be treated as one and combined with a third kite, etc.

Thus far our consideration of tandem flying has been confined wholly to the question, how much effect can be produced by a certain *pull*, and we have found that the maximum elevation is attained either by concentrating the pull wholly at the outer end of the line) and this is the only feasible arrangement) or by acting with a portion of the pull upon each particle of the wire just as gravity acts to pull it down.

Best utilization of a given line.—We will next consider the second question that arises in connection with tandems, namely, how to best employ a line of given strength to attain elevation. If we attach at the end of the given line a kite so large that its pull strains the line to its safe working limit, a second kite can not be attached without danger to the line, except at some point well down upon the line, where, by reason of the diminution of the tension in the line corresponding to its deeper and deeper sag, the combined pull of the two kites will not exceed the safe working strength of the line. The second kite can not, in any case, pull as much as the first kite, but may be larger and larger the more and more the line is permitted to sag. Equation (28), inverted, tells us how much a kite it is proposed to add, can pull without exceeding the strength of the line; t_2 in that equation becomes T, the working tension that the line can sustain; θ is the direction or inclination of the pull to the horizontal; θ' is the inclination and t' the tension of the wire at the point where the second kite is to be attached. The pull of the top kite has already been assumed to be $T=$ the strength of the line, and if θ'' is the inclination of this pull, then since

$$t' = T\frac{\cos.\ \theta''}{\cos.\ \theta'} = TR_1,$$

we get,

$$t = T\left[\sqrt{1-R_1^2\left(1-\cos.\ (\theta-\theta')\right)} - R_1 \cos.\ (\theta-\theta')\right] \quad (31)$$

Equation (31) shows that the second kite can pull the hardest if it is attached where the main line has sagged down to the horizontal condition; that is, where $\theta' = 0$; but we have already found that this is the opposite of the conditions that must be satisfied to attain high elevations. The final conclusions are plain, namely: (1) To utilize a given pull to the best advantage it must be concentrated at the end of the line; (2), to attain the maximum elevation with a line of a given strength every part of it must be subjected to the maximum strain that it can sustain. In other words, we must attach the largest kite the line can carry at the top end, and then little by little, as the line sags and the tension thereon diminishes, the tension must be increased up to the

safe limit by additional kites. Equation (31) applies broadly to all cases, and is independent of the weight of the line per unit length, which means that we need consider only T, the maximum safe working tension of the particular line that is employed, thus embracing the case where fine lines at the start are joined to stronger lines as the pull increases.

The wind-impressed catenary.—The special results brought out in the foregoing application of the properties of the catenary to kite flying are not strictly the exact results that will be attained in practice, because we have neglected to include the effect of the wind upon the wire, as we are forced to do by the limitation of our knowledge concerning its pressure upon long fine wires. It seems that some knowledge of this total effect might be gained by a comparison of the actual behavior of kites whose constants are fully known with those effects which our knowledge of the properties of the catenary show should result. The experimental work of the Weather Bureau has not as yet been carried sufficiently far to furnish data of this nature, but the matter has been carefully considered from this standpoint with a view of deducing what may be called a correction for wind effect on the wire.

The general nature of the action of the wind upon the wire, and its effects in modifying the catenary may be shown in a more or less satisfactory manner, as follows: Let Fig. 79 represent a catenary subjected to the action of the wind. Along the lower portions of the curve the wind effect is very slight, both because the inclination of the wire is small, and as a rule, the force of the wind near the ground is less than throughout the upper portions of the curve where the effect of the wind pressure upon the wire will be greater, both because of the steeper inclination of the latter and the greater force of the wind. We can not conceive that any appreciable friction arises in the flow of the wind over the wire, and as a result the wind pressure must be normal to the wire at every point. Let the pressure upon a small element of the wire at p be represented by the line $p\ v$. Also let $p\ g$ represent the weight of the same element. The effect will then be the same as if the element in question were acted upon by a single force $p\ r$, which is the resultant or combined effect of the two forces of wind and gravity. Drawing in a similar manner the resultant pressure at other points of the curve we see that the curve assumed by the wire must be one that results from the action of a nearly constant force, which tends to press the wire in a direction such as $P\ R$. If we consider only a portion of the catenary $A\ B$, such as might be involved in a partial ascension, we may plainly, with but little error, assume that the combined effects of wind and gravity act in the direction $P\ R$. In such a case the resulting curve will be sensibly the same as would result if we imagine that gravity alone acted, not in a vertical direction, but in the direction of the line $P\ R$. In other words, the general *form* of the curve will be given by the equations we have already deduced, if we im-

agine the origin of coordinates to be shifted to a new position as $O' Y'$, $O' X'$, which are parallel and perpendicular to the line $P R$. The *tension*, also, will be given approximately by those equations if we imagine w to be increased in proportion to the ratio of the lines pr to pg.

A very simple way of experimentally studying the effects that result from shifting the origin of coordinates in the manner mentioned as applied to kites, consists in laying off on a drawing board an inclined line, $A B$, representing the angular elevation of the kite under consideration. Draw $A B'$, forming the angle θ' with the horizontal, and representing the inclination of the wire at the reel. Placing the drawing board on edge and suspending a small chain next its surface we may produce in a beautiful manner the curve of the catenary that shall make the angle θ' at the reel, and we may locate its point of crossing the line at B. Fixing these points of the chain by pins or otherwise, it will be found that by raising one edge so that the board stands on its corner, thereby inclining the line $A B$ at different angles in a vertical plane we cause important changes in the inclination of the chain at its fixed points. In order to restore the original inclination, preserving still the same length of chain between the points $A B$, and the upper extremity of the chain upon the line $A B$, it will be found necessary to make the end B approach A as the line $A B$ is made more and more nearly horizontal. These suggestions suffice to show a very simple method that has been employed in several ways by the writer to study the wind affected catenary.

Until the experimental observations have given accurate data concerning the magnitude of the wind effect, it will not be desirable to attempt to deduce equations representing the combined action of wind and gravity. This interesting and important branch of the kite problem must be left for solution in the future.

In this discussion of the theory and practice of flying kites for scientific purposes, the writer has aimed to show how the well known forces of nature act in producing the more important effects commonly observed in kite flying and to point out those general and fundamental principles of physics and mechanics pertaining to kites, by the proper application of which principles we may expect to secure the maximum useful results according to the requirements of any particular case. The groundwork we have aimed to lay for this work is not as complete as we could wish, owing to the limited time available for the Weather Bureau kite experiments, but it is hoped to extend the work to more promising forms of kites than those that have thus far been employed.

The Editor of the Review has shown a deep personal interest in both the kite experiments themselves and in the publication of this series of articles in the Review and the writer wishes to acknowledge the benefits that have resulted from his careful revision of the manuscript and proof.

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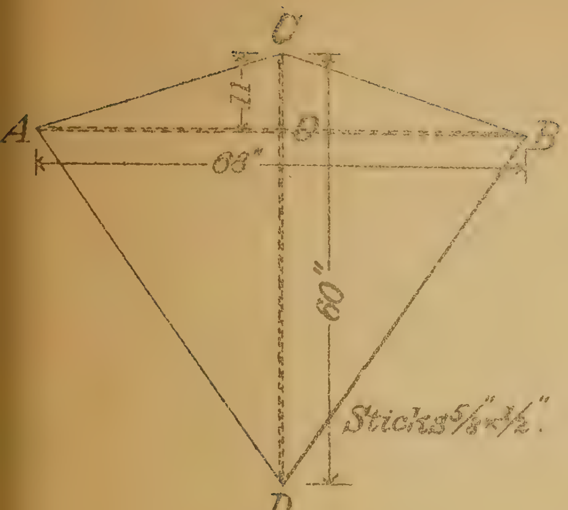


Fig. 1.

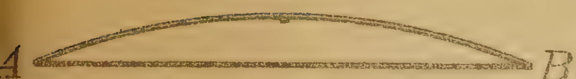


Fig. 2.

Fig. 4.

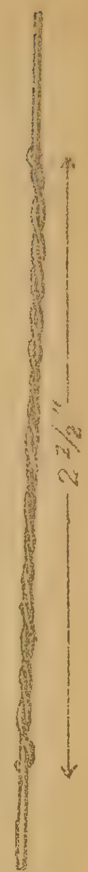
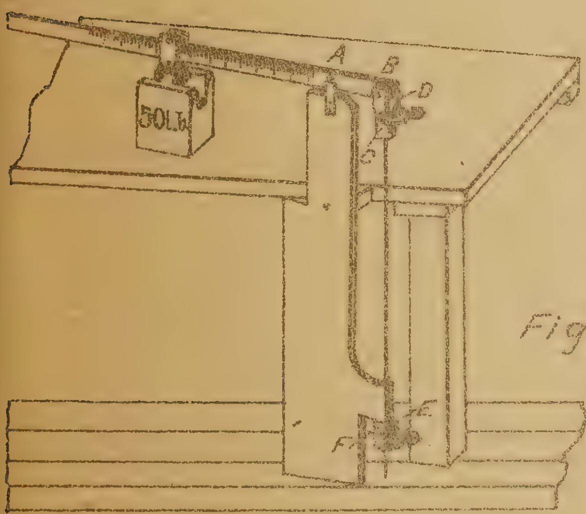


Fig. 5



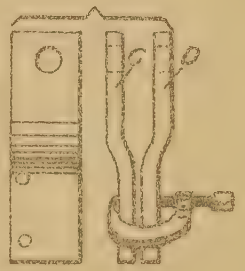


Fig. 3.

Fig. 7.

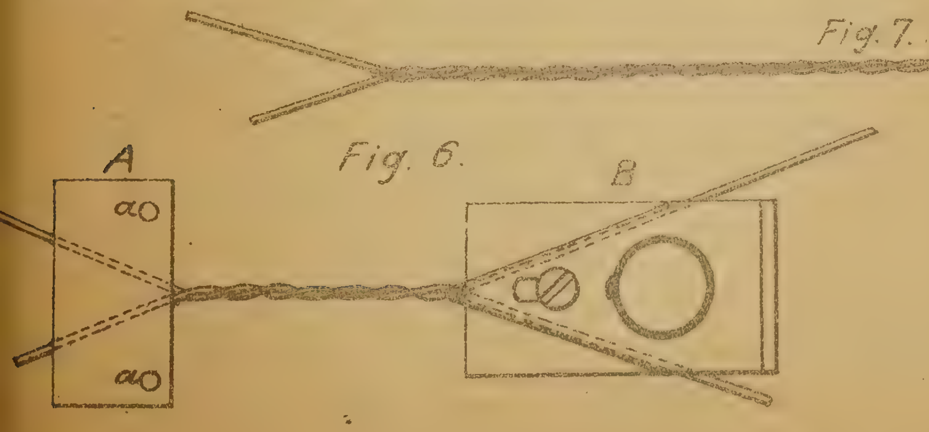


Fig. 6.

Plate II.

Fig. 8.

Double overhand knot and loop.

Fig. 9.

Sheet bend.

Fig. 10.

Sheet bend, double turn.

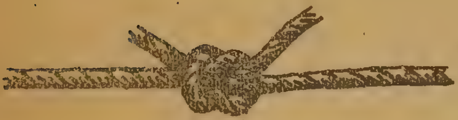


Fig. 11.

Square knot.

Fig. 12.

Fisherman's knot.

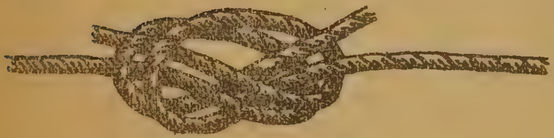


Fig. 13.

Interlaced overhand knot.

Fig. 14.

Figure of 8 knot.

Fig. 15,

Carrick's bend.

Fig. 16.

Bowline knots.

Plate III.

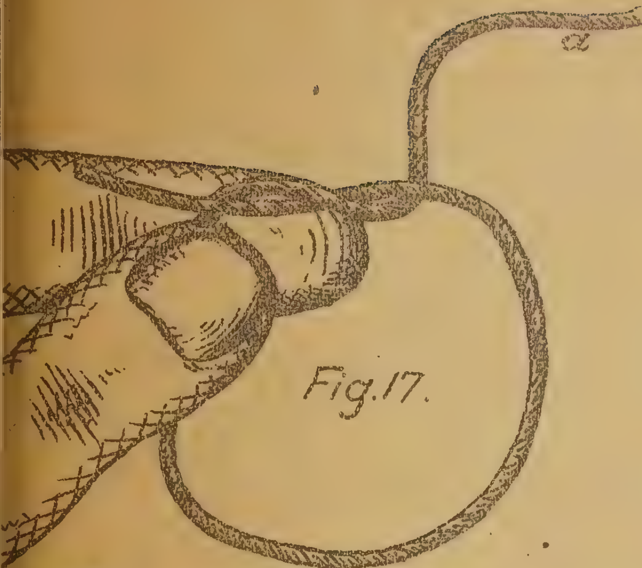


Fig. 17.

Fig. 18.

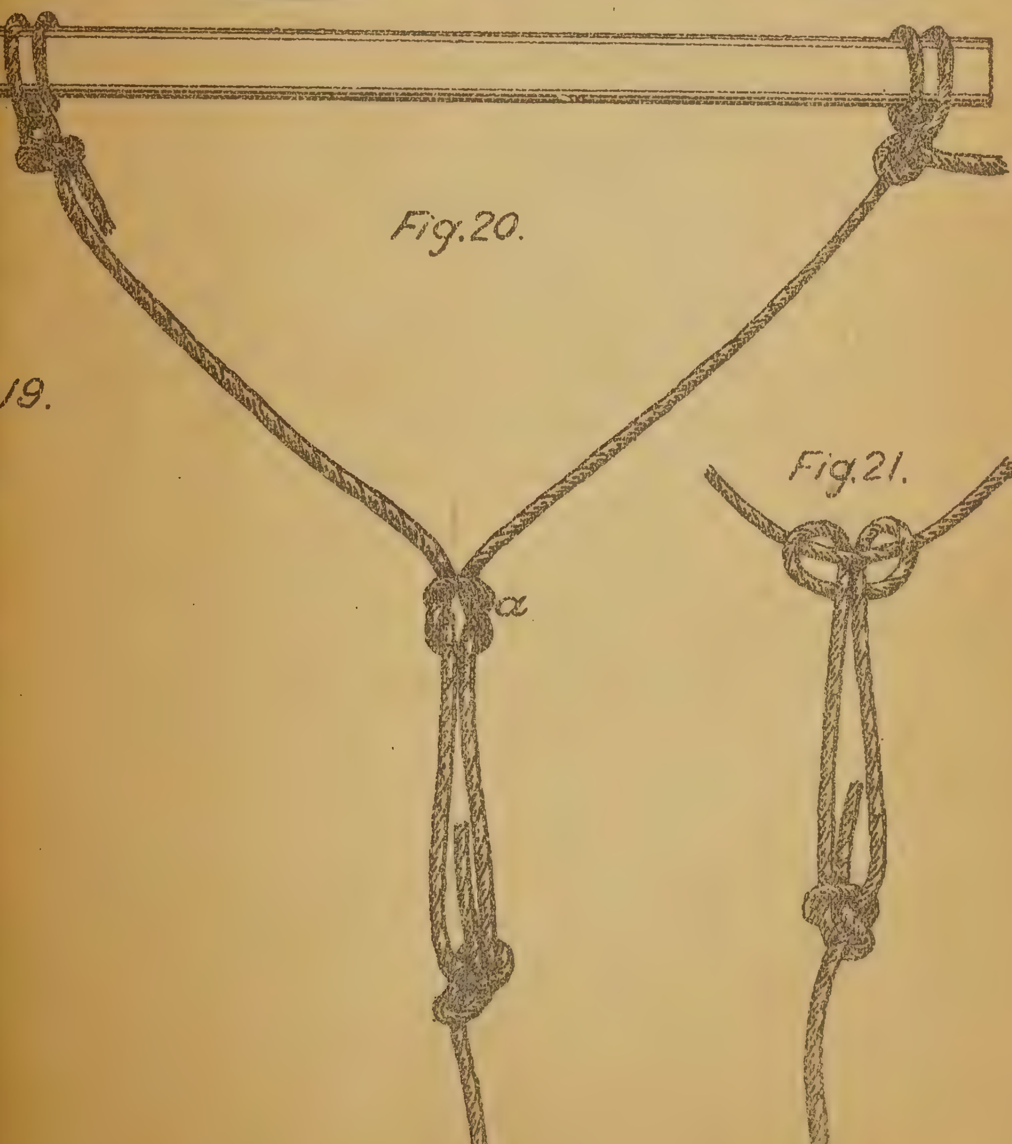


Fig. 20.

ig. 19.

Fig. 21.

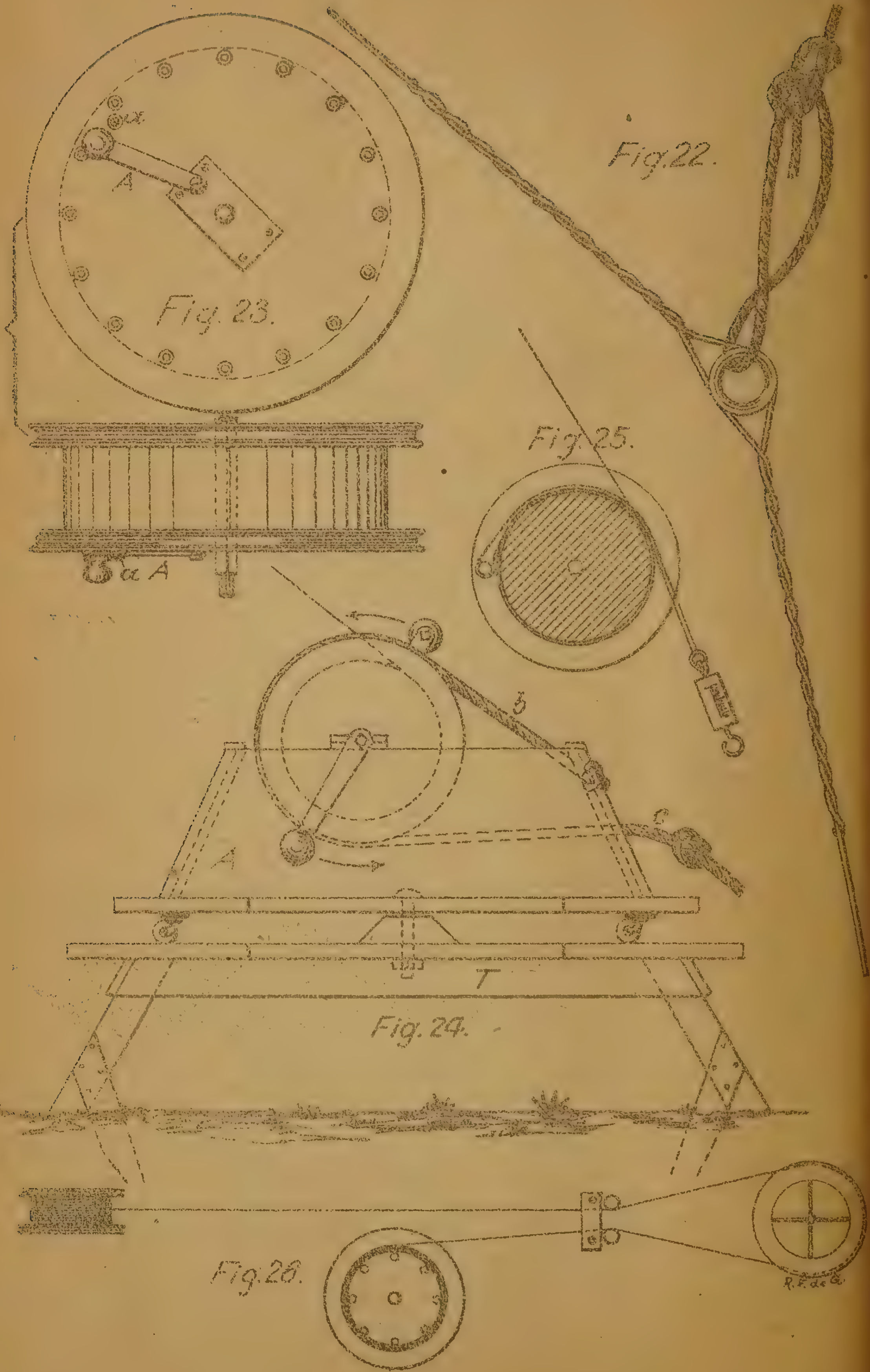


Fig. 22.
Fig. 23.
a
A
a A
Fig. 25.
b
c
A
T
Fig. 24.
Fig. 26.
R.F. de G.

Plate V.

Fig. 27.

Fig. 29.

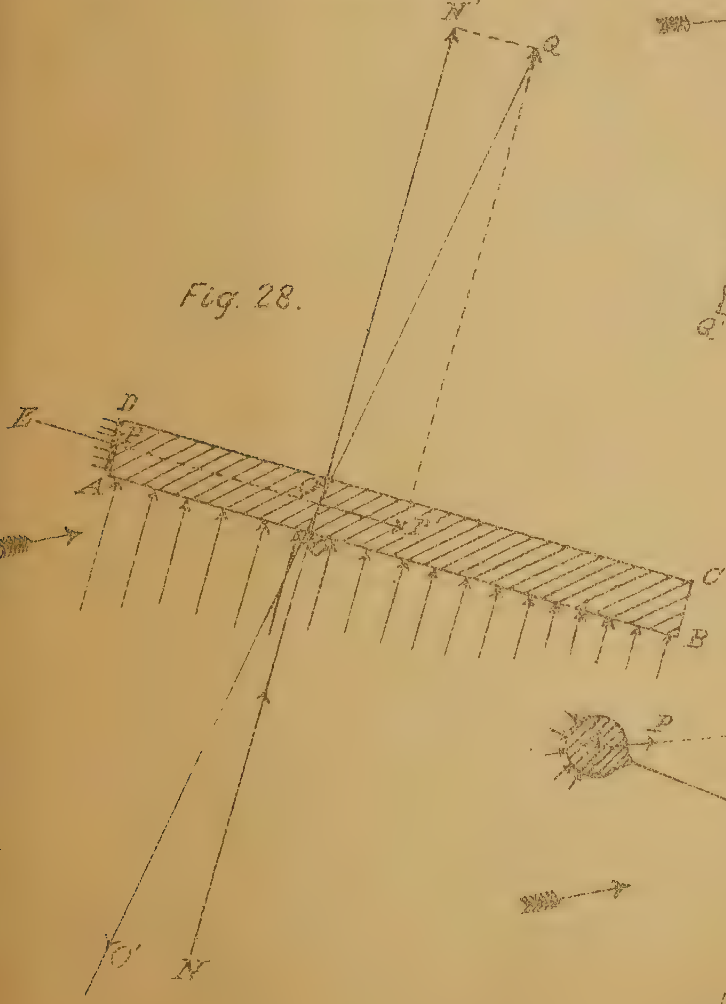
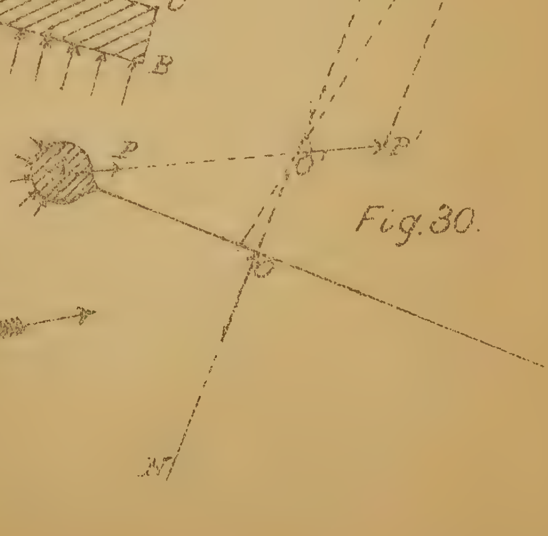


Fig. 28.



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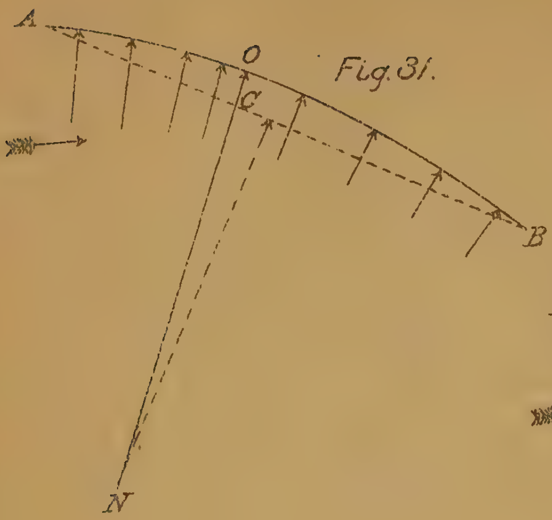


Fig. 31.

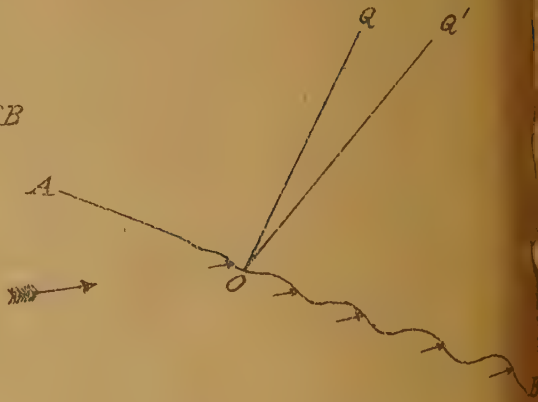


Fig. 32.

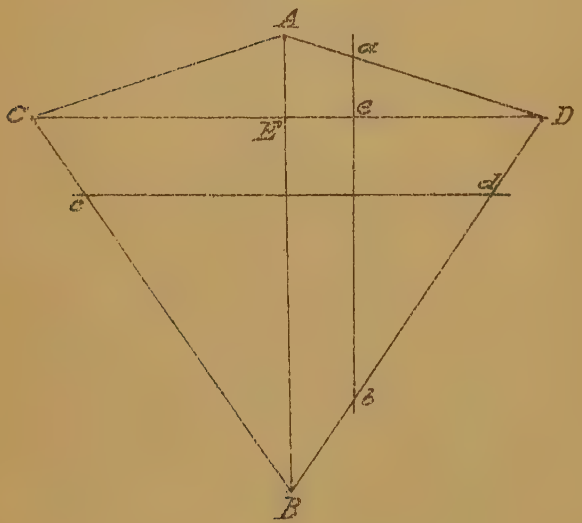


Fig. 33.

Fig. 35.

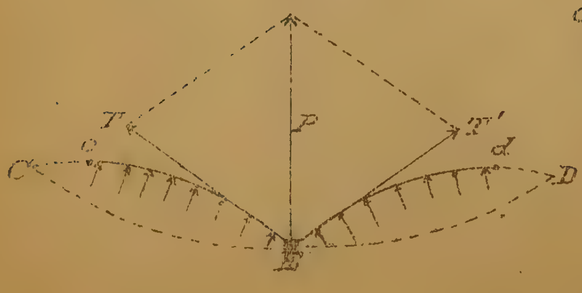
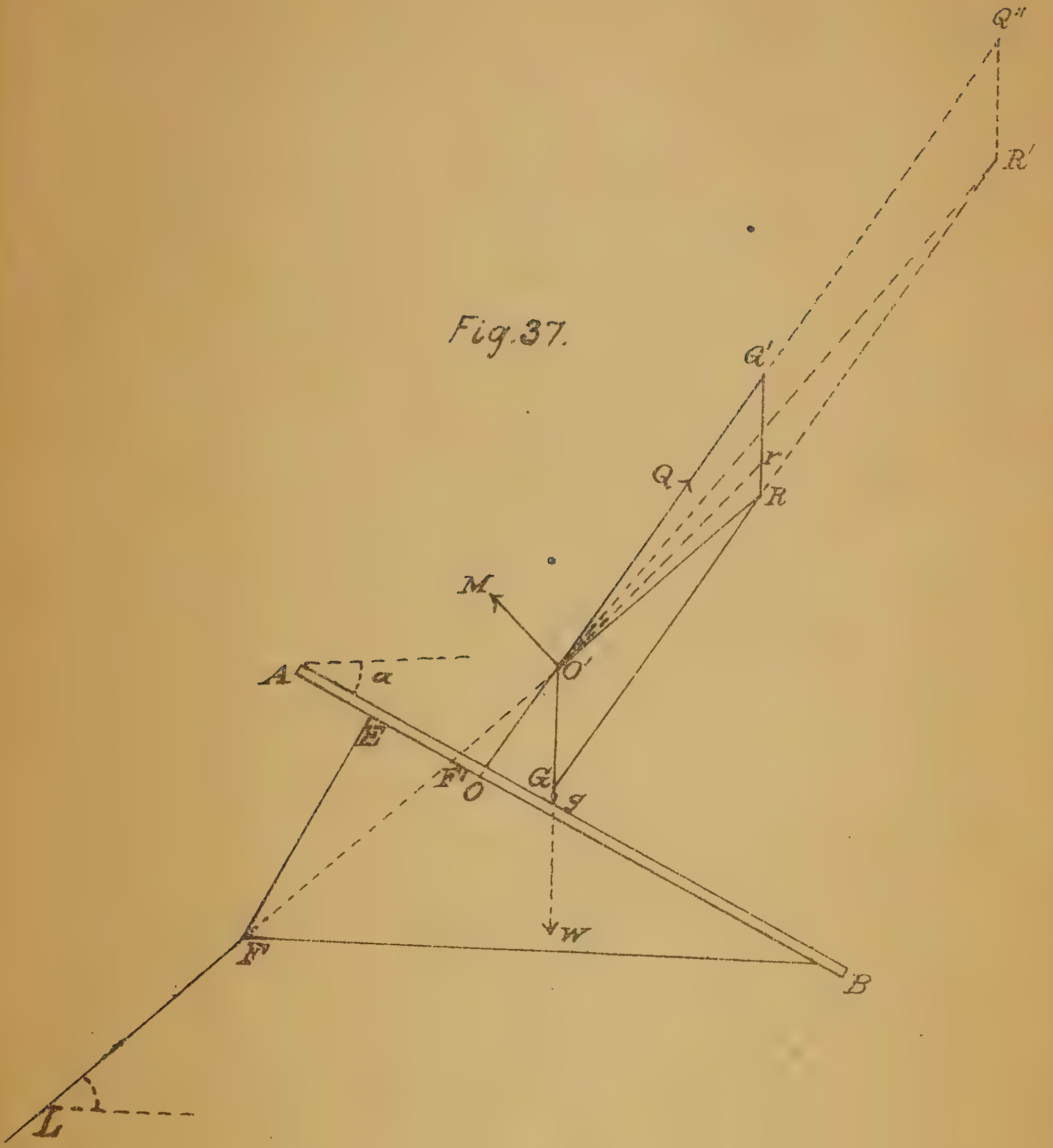


Fig. 34.

Fig. 36.



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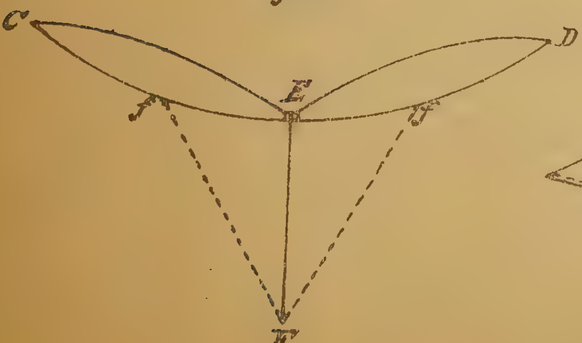

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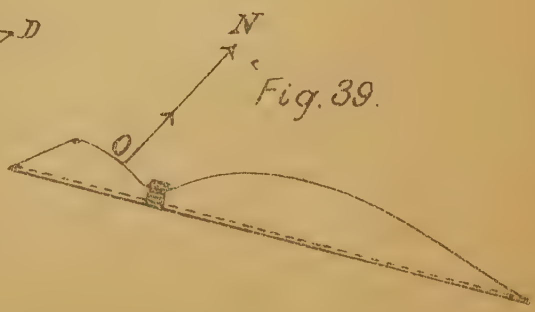
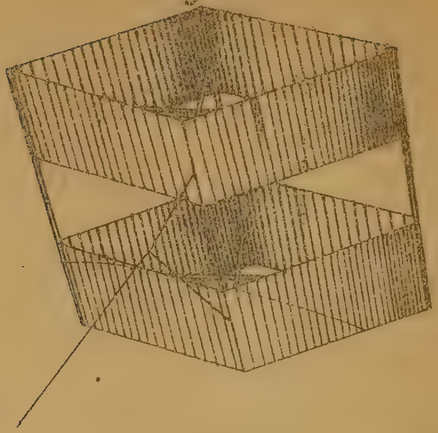


Fig. 39.

Plate VIII.

Fig. 40.



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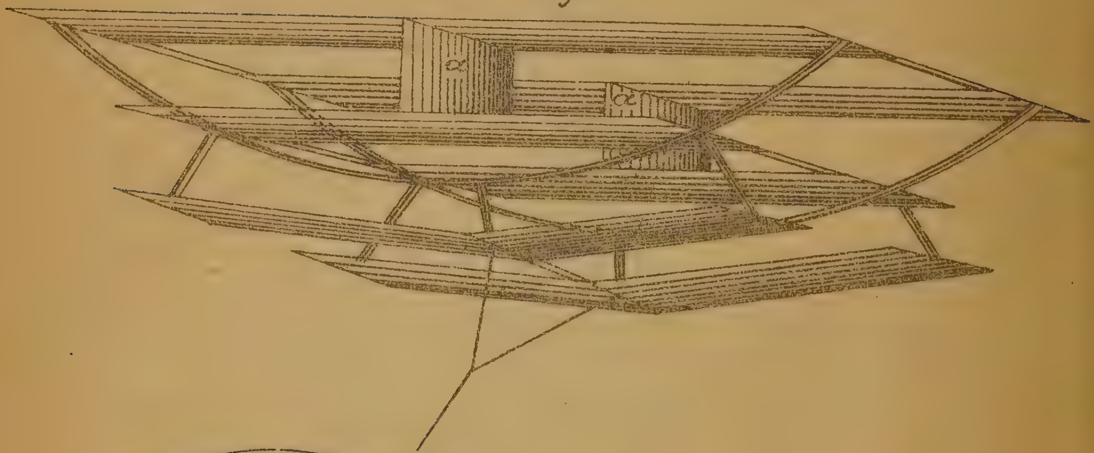

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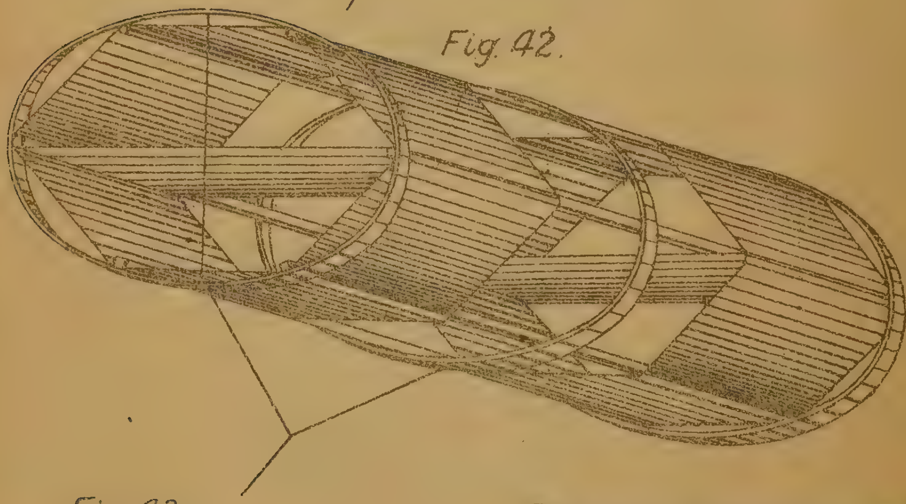

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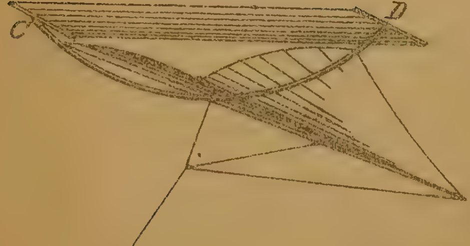


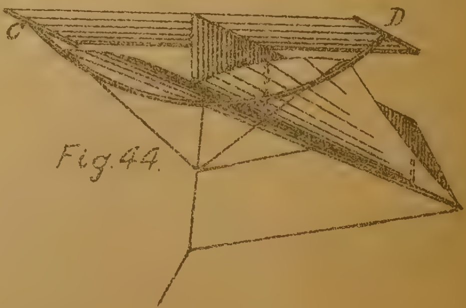


Fig. 44.

Plate IX.

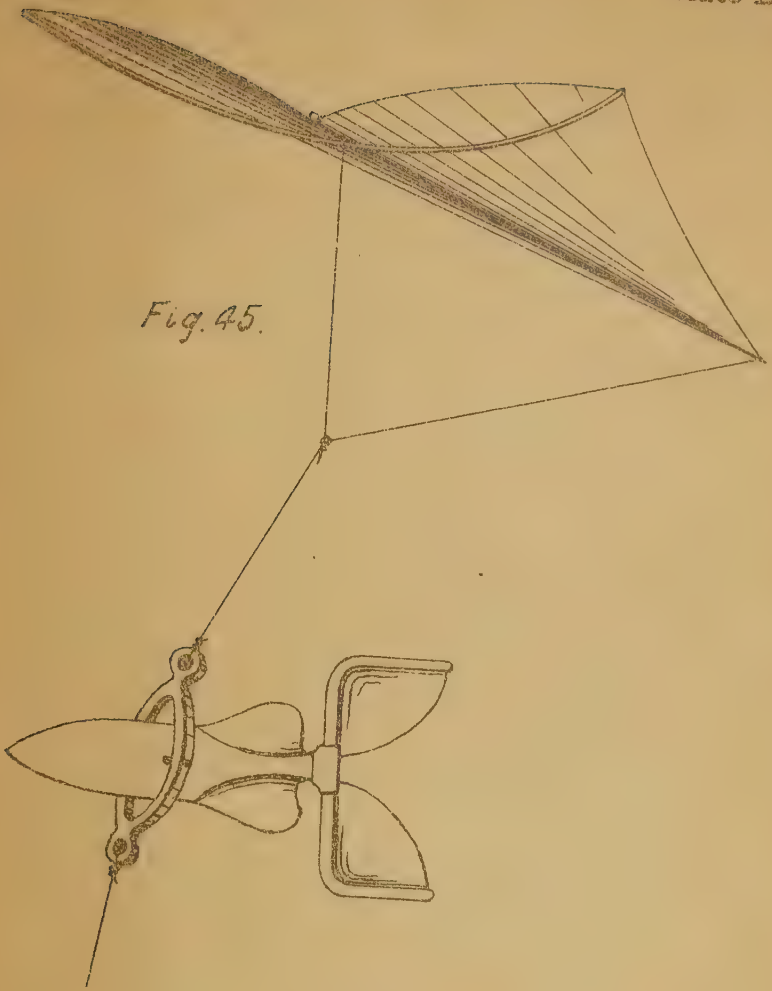
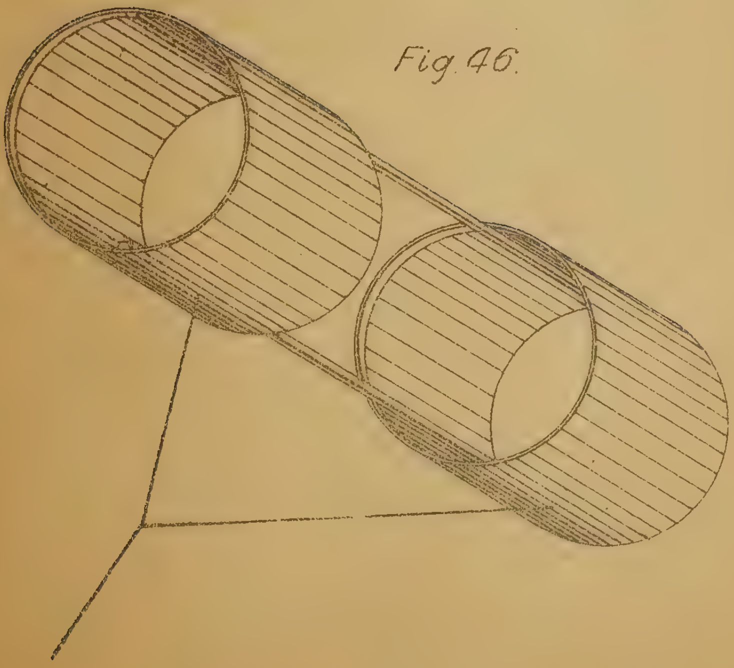


Fig. 45.

Fig. 46.



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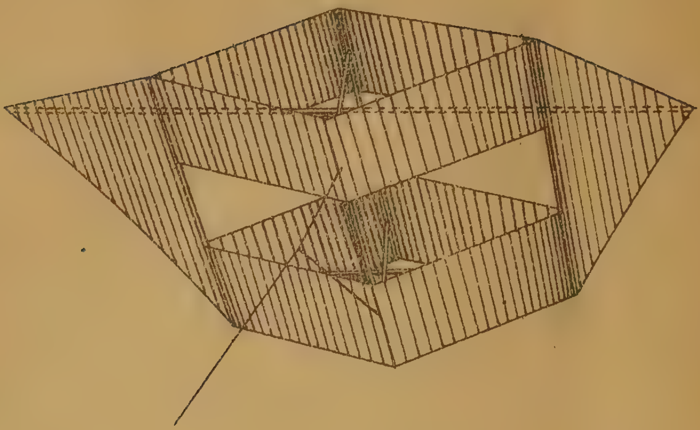

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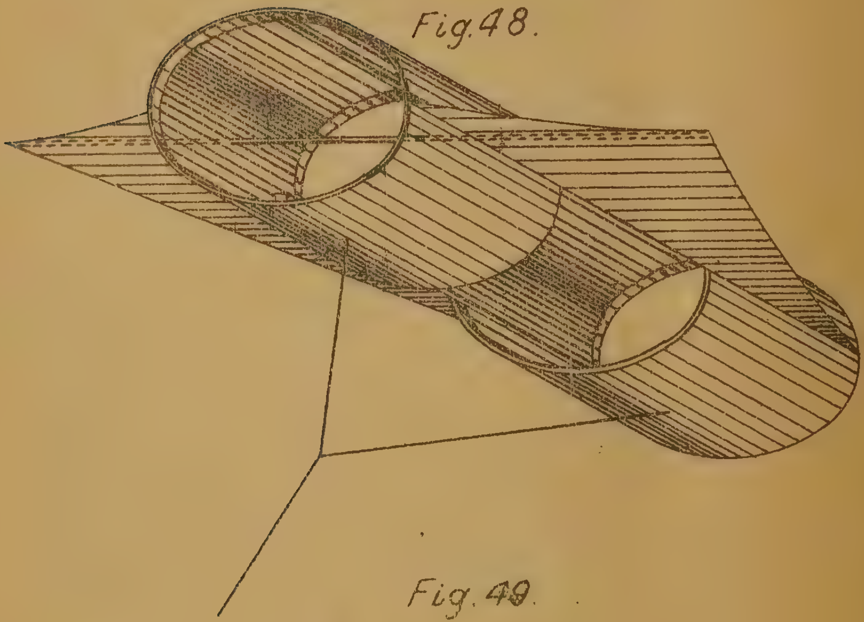

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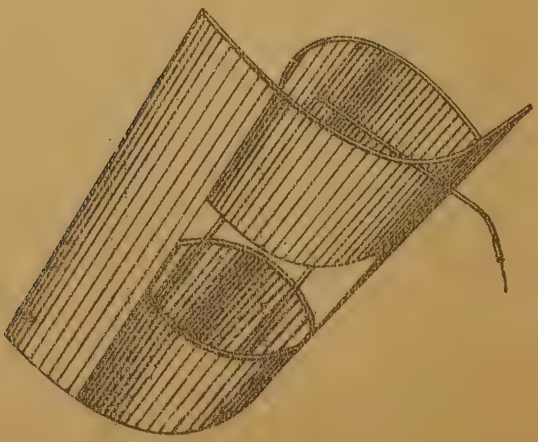

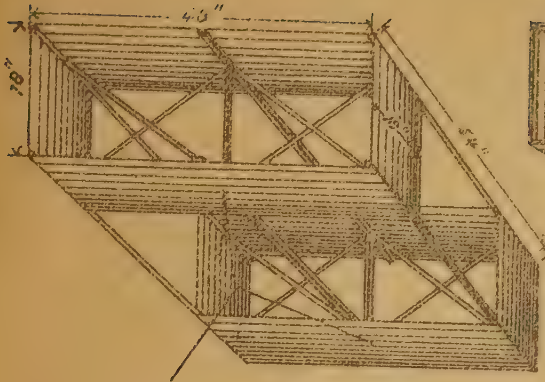

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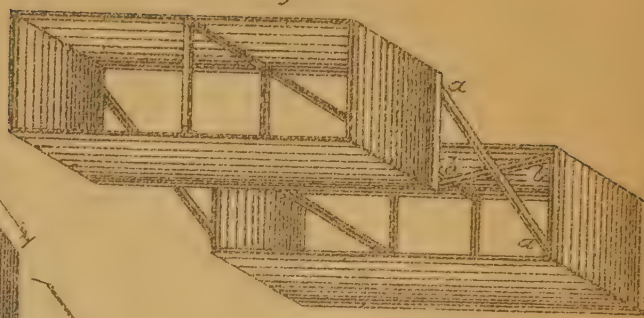
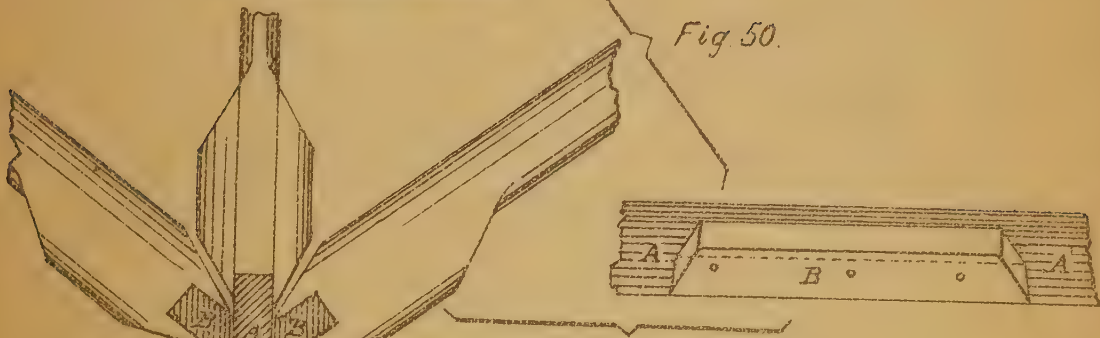
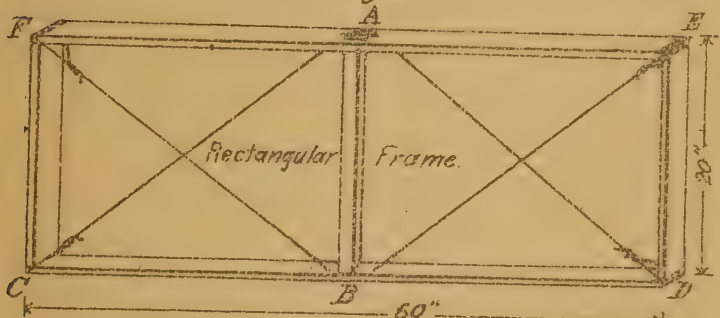


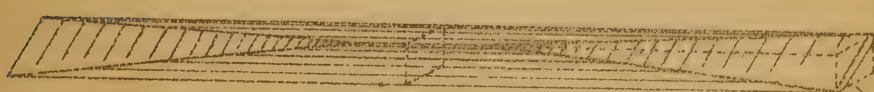
Fig. 50.



Detail of Struts at Midrib.

Fig. 52.





Frame Connector.

Fig. 53.

Angle tin attached to Connector.

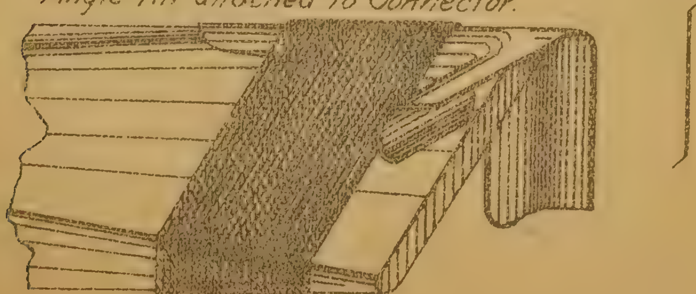
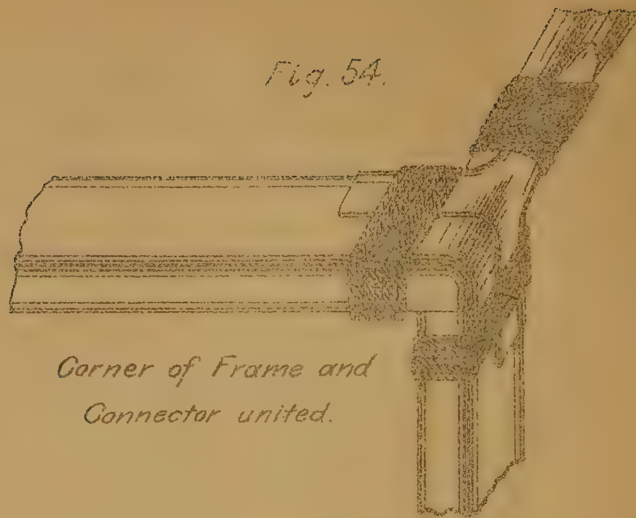
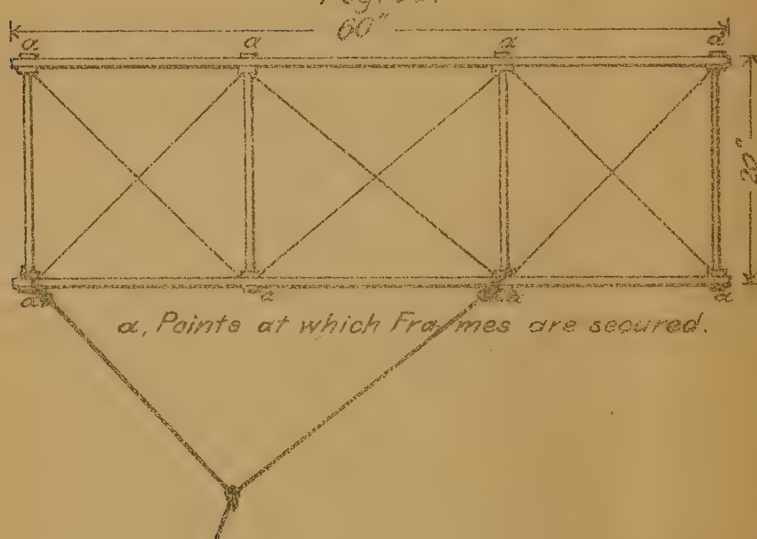


Fig. 54.



Corner of Frame and Connector united.

Fig. 55.



a, Points at which Frames are secured.

Fig. 56.

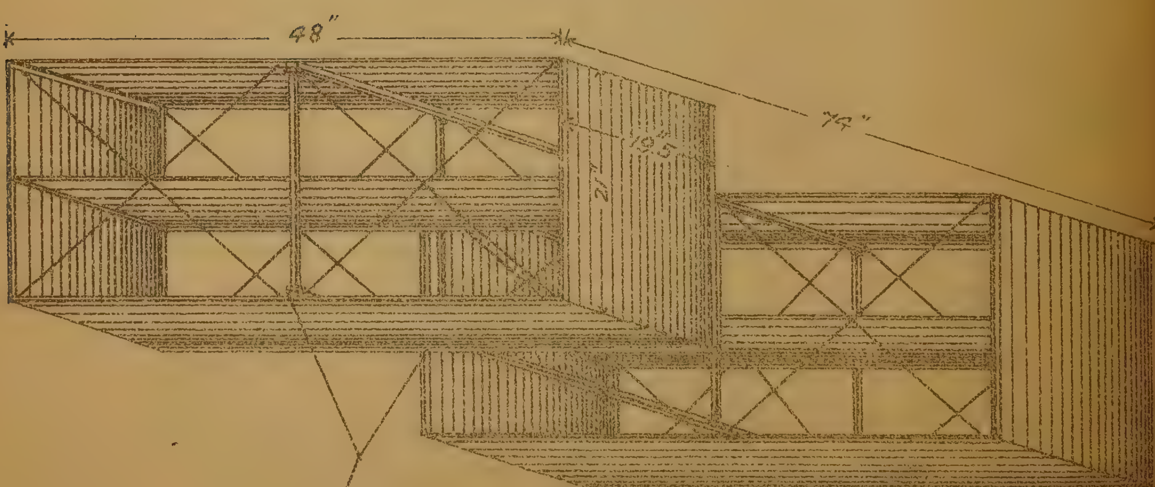


Plate XIII.

Fig. 57.

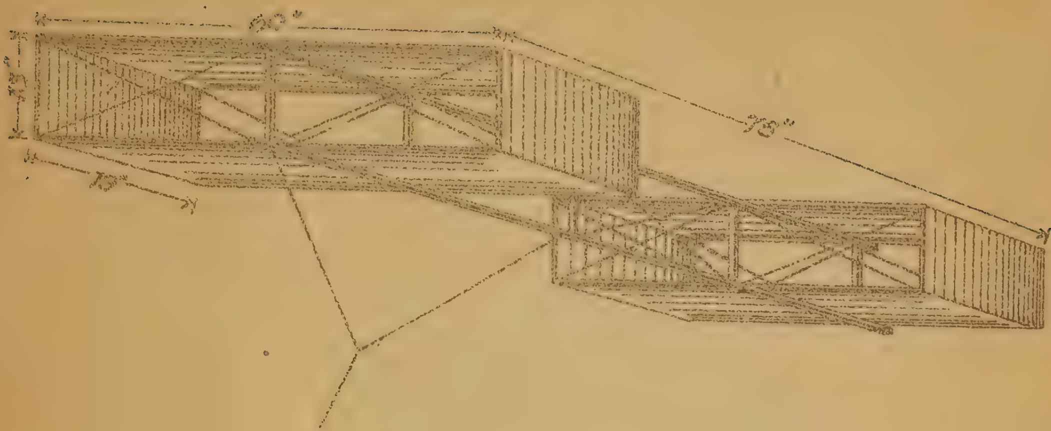


Fig. 58.

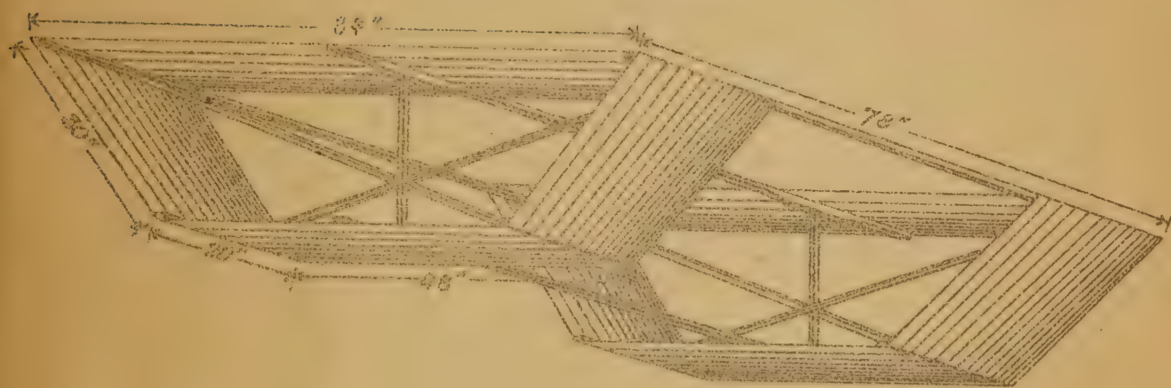
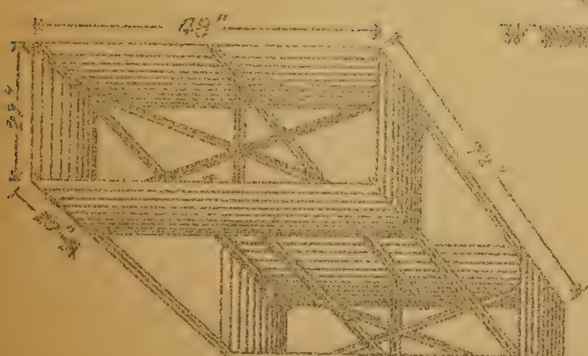
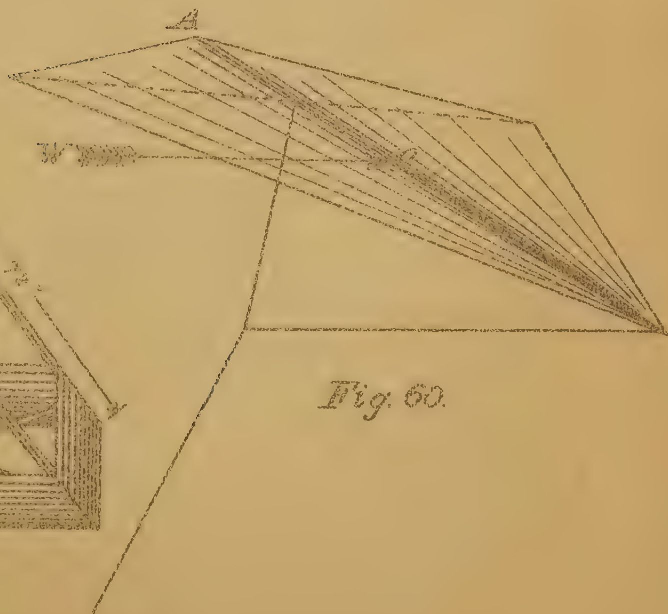


Fig. 59.





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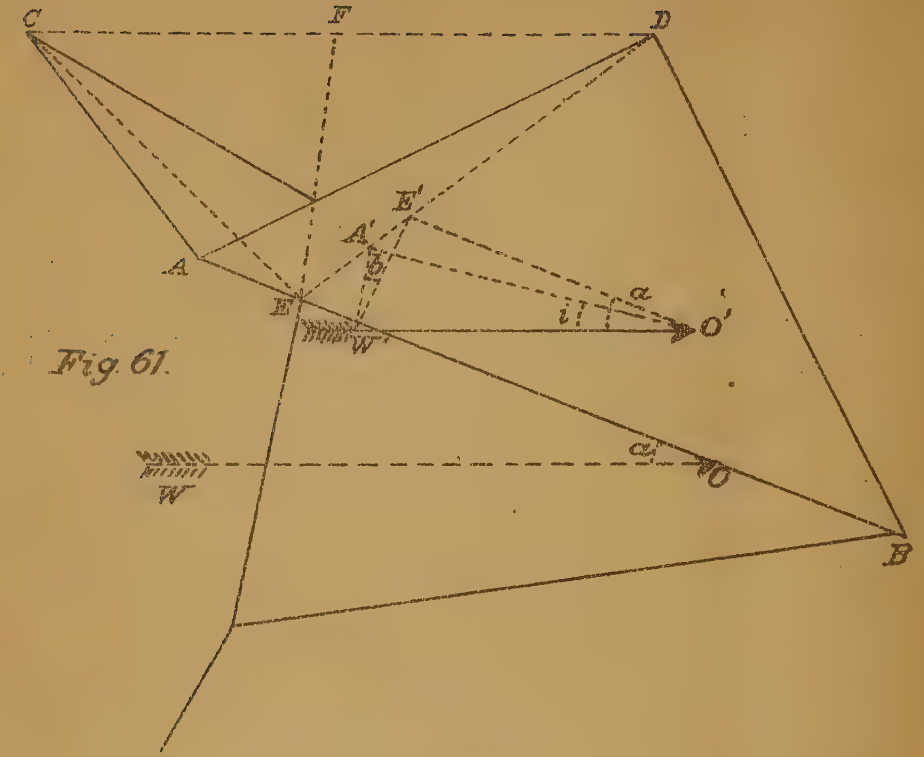

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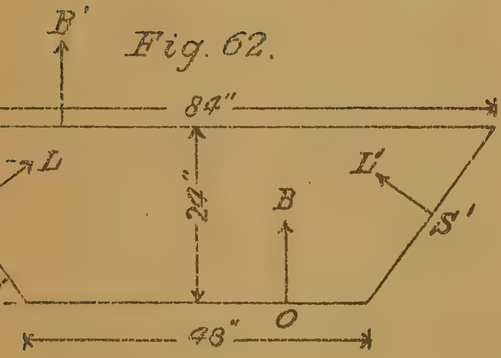
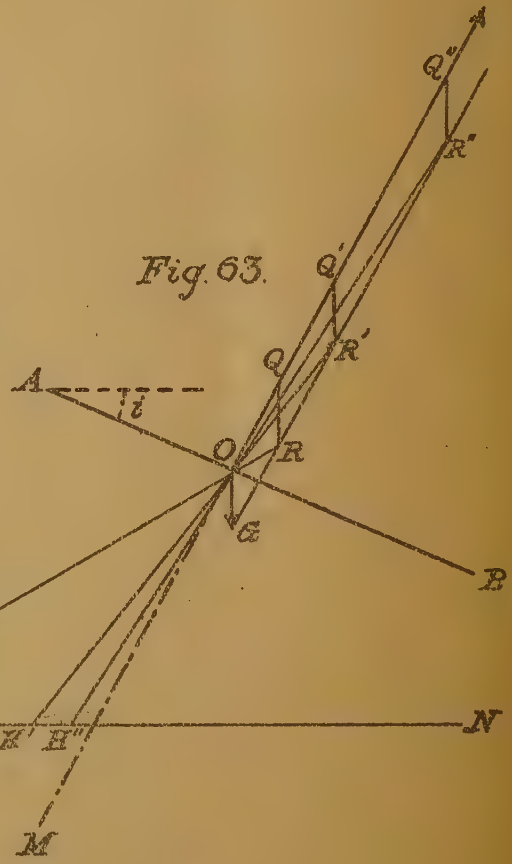


Fig. 62.



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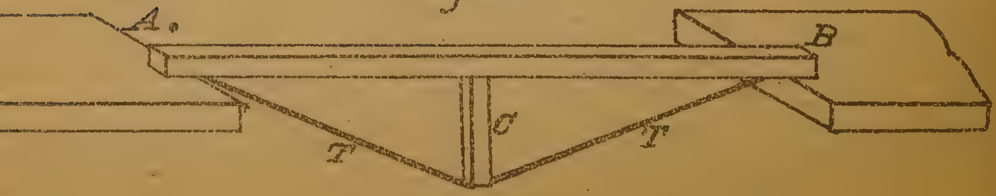

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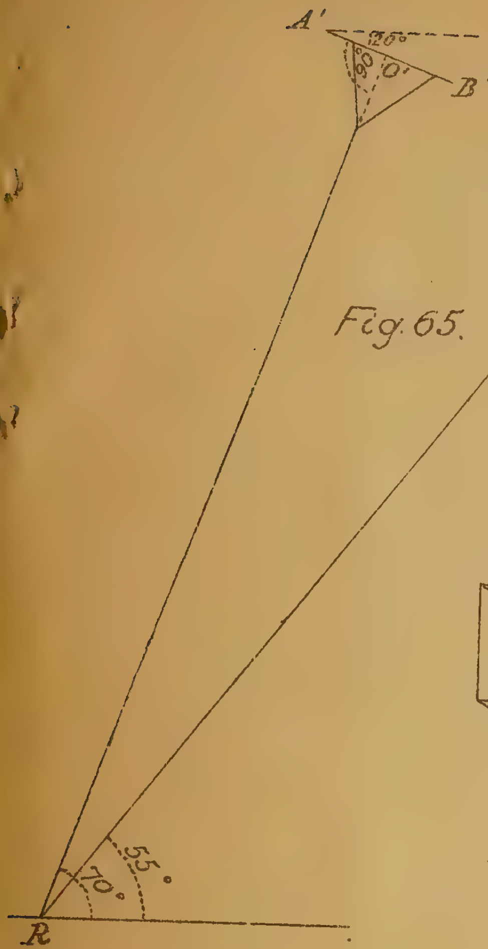
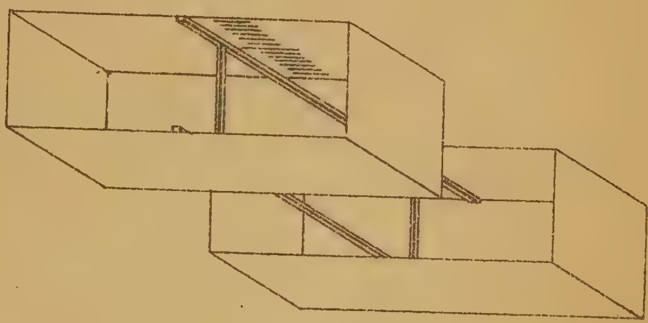


Fig. 65.

Fig. 66.



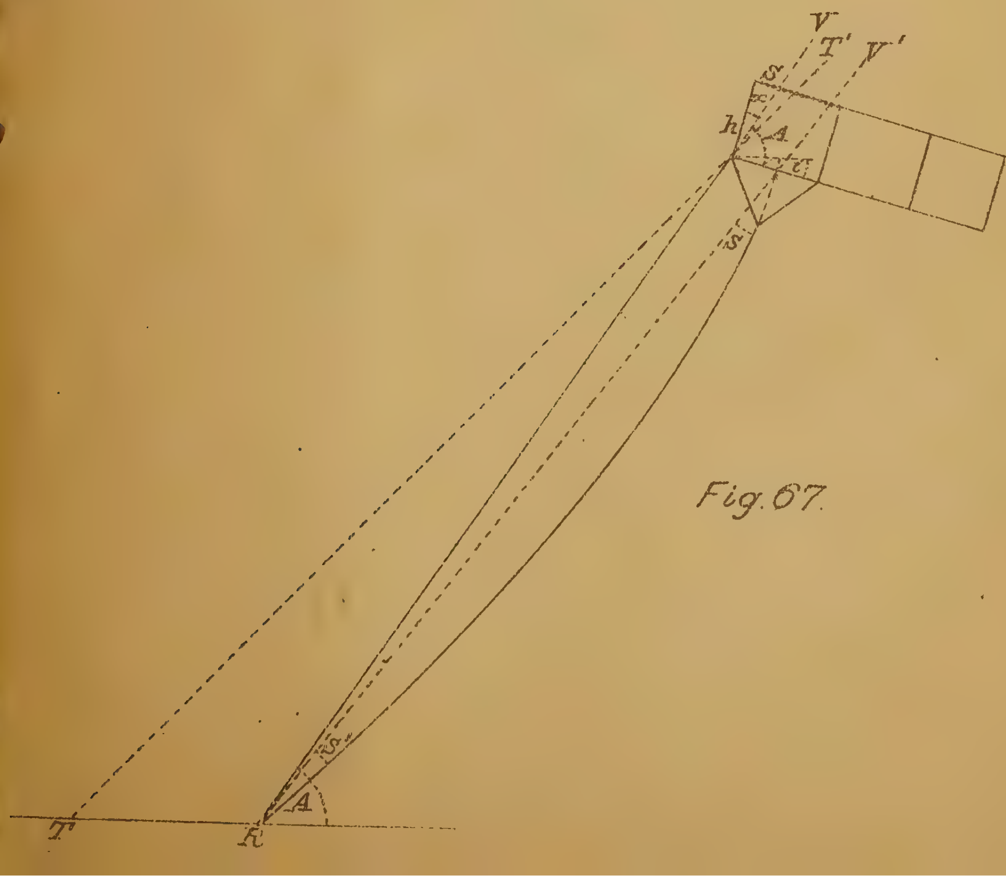
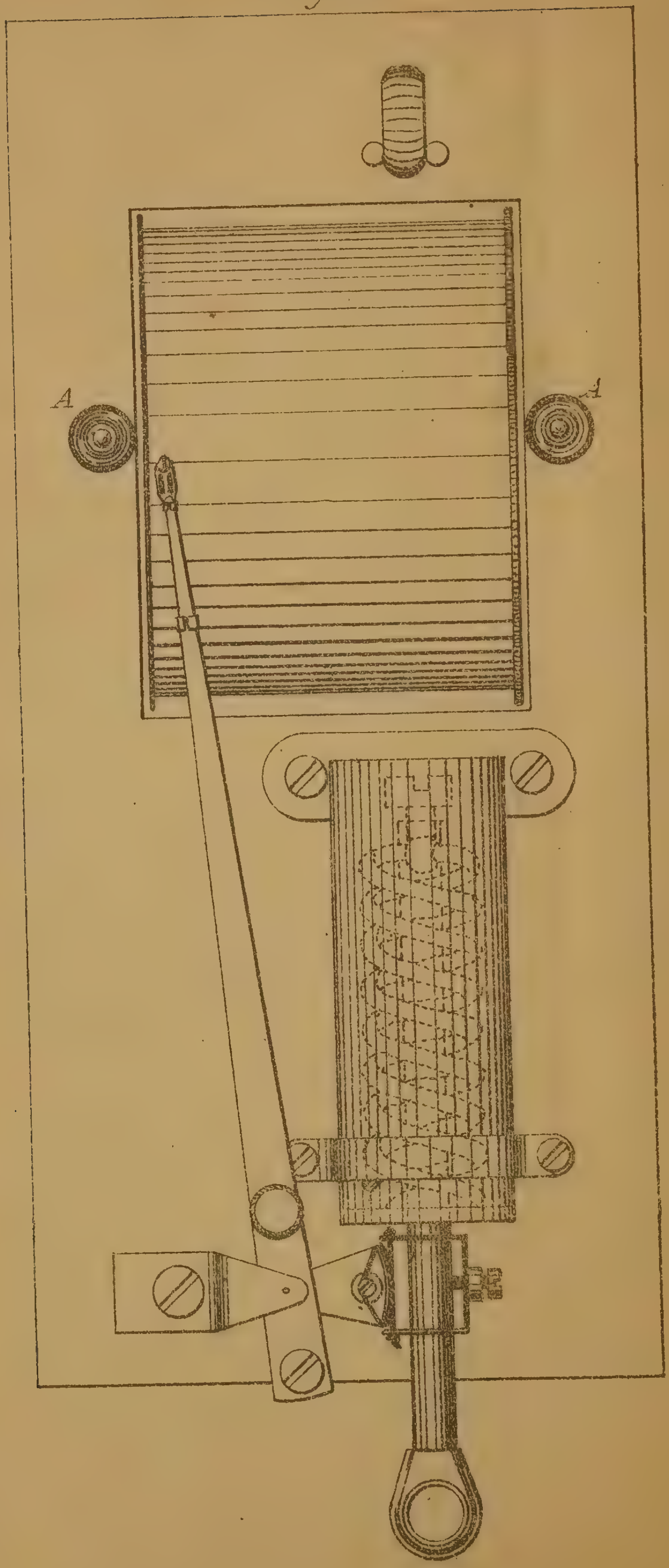


Fig. 67.

Fig. 68.



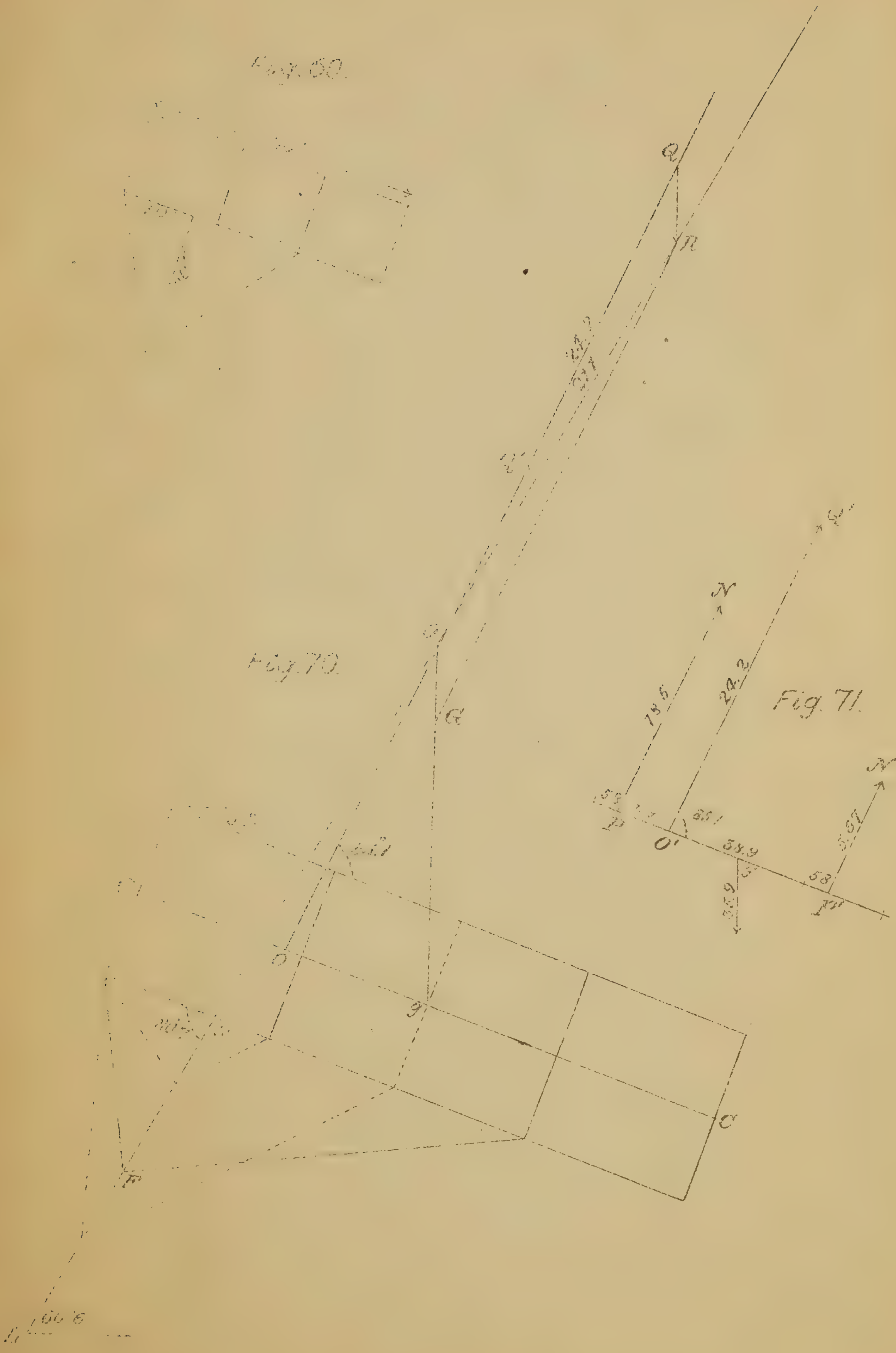


Fig. 69.

Fig. 70.

Fig. 71.

Plate XVIII.

Fig. 72.

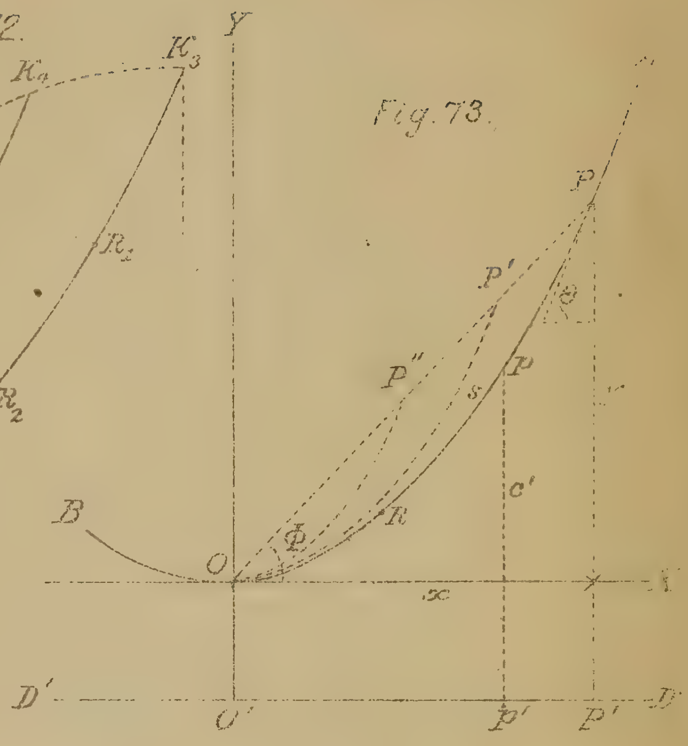
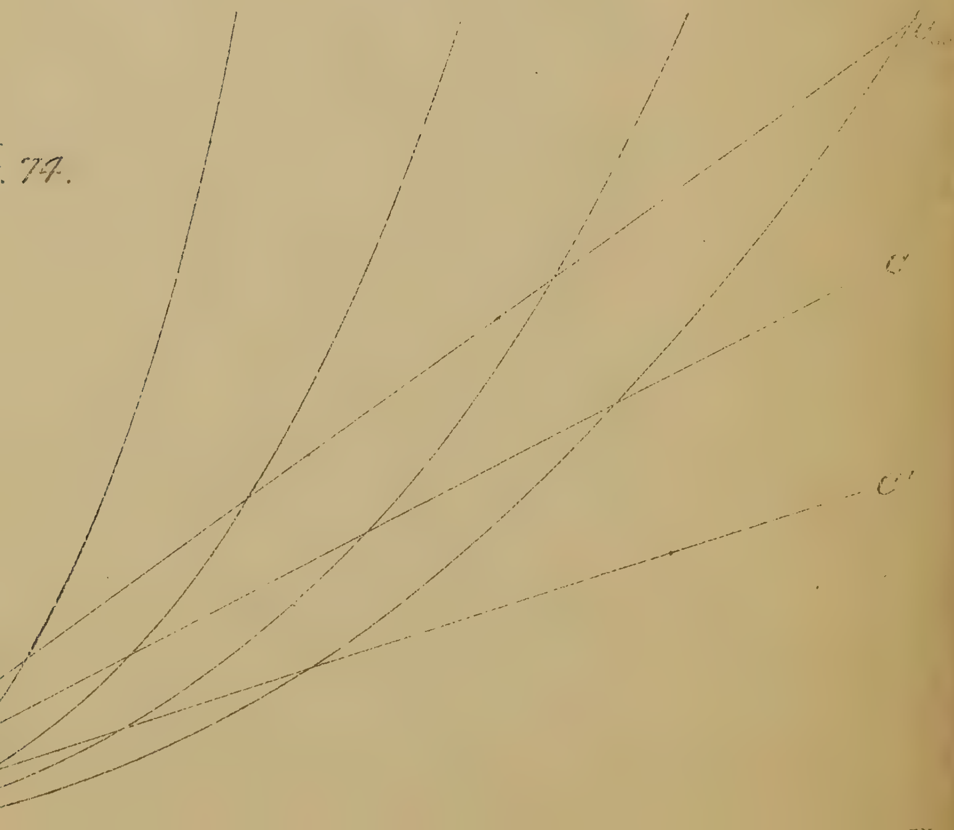


Fig. 73.



.74.

Fig. 75

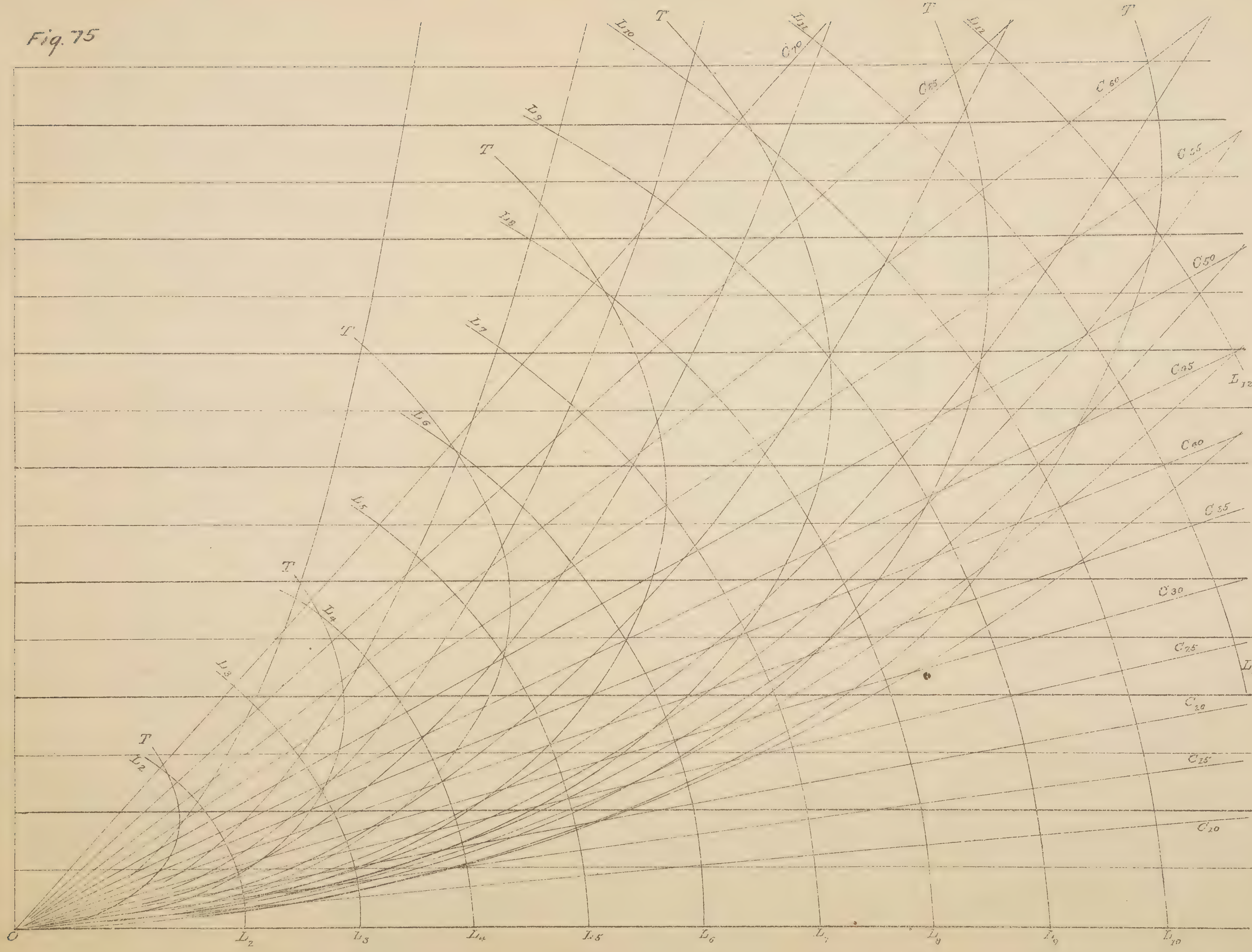
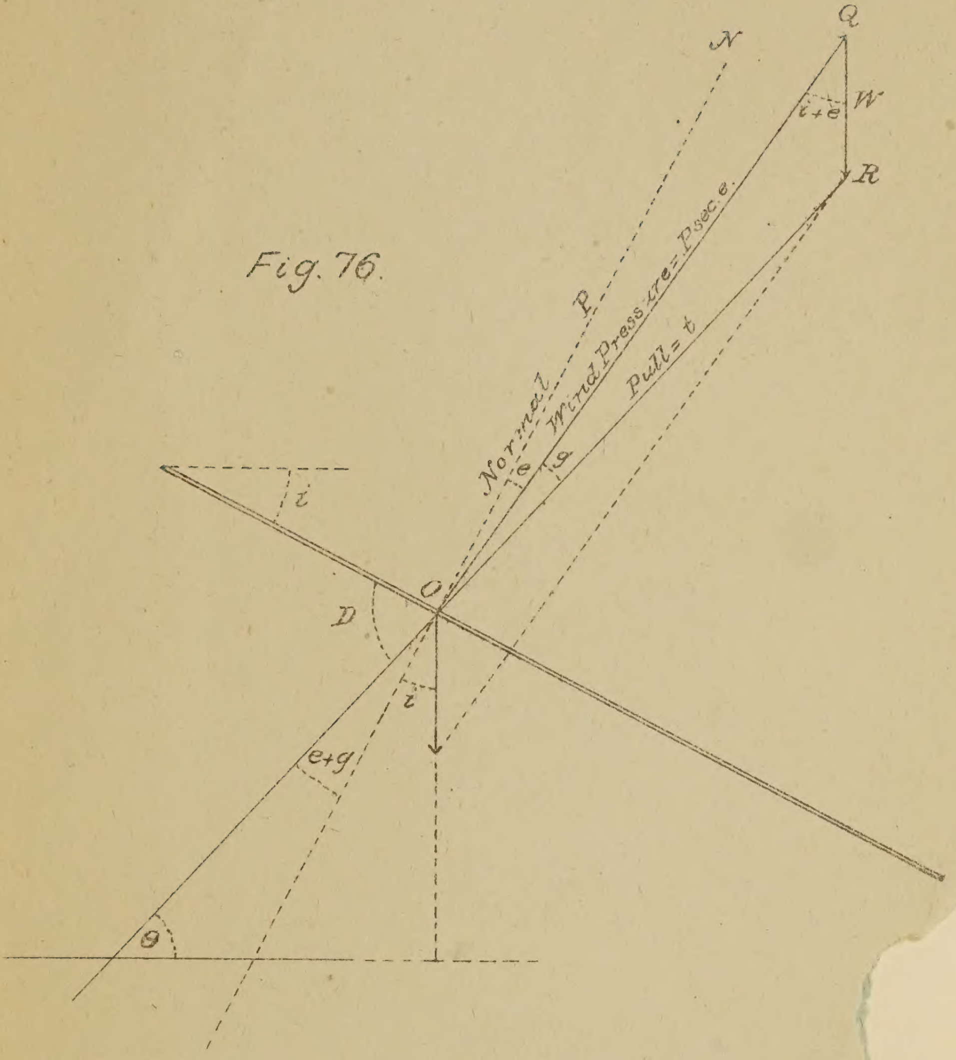

T
L2
L3
L4
L5
L6
L7
L8
L9
L10
L11
L12
C10
C15
C20
C25
C30
C35
C40
C45
C50
C55
C60
C65
C70
O

Plate XX.



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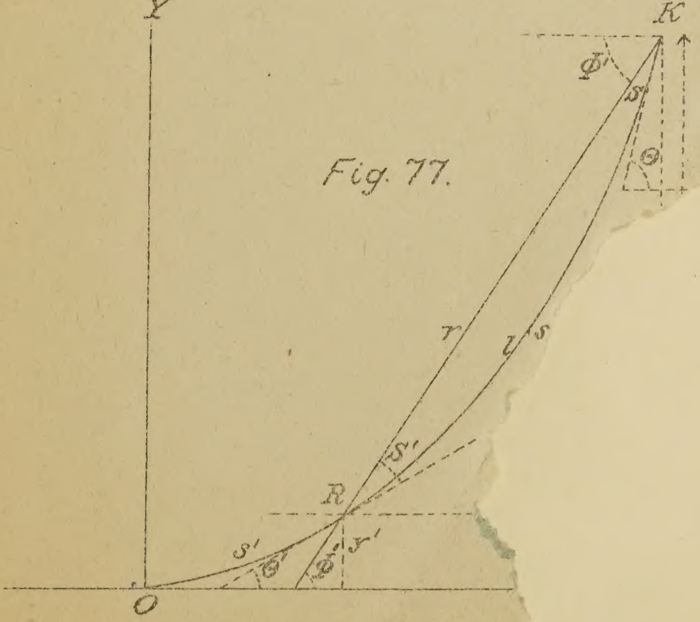

Fig. 77.

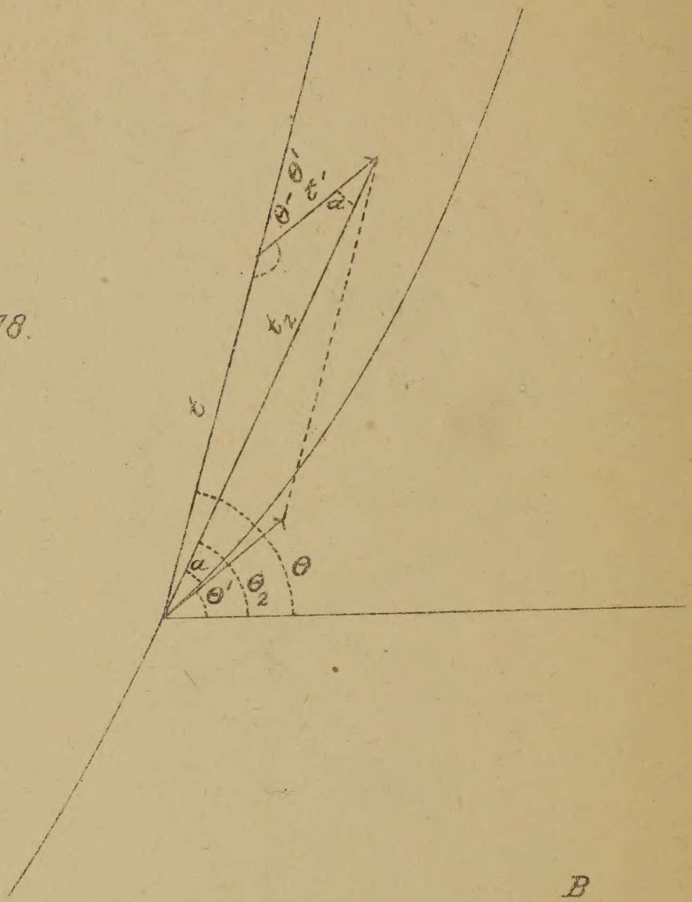

Fig. 78.

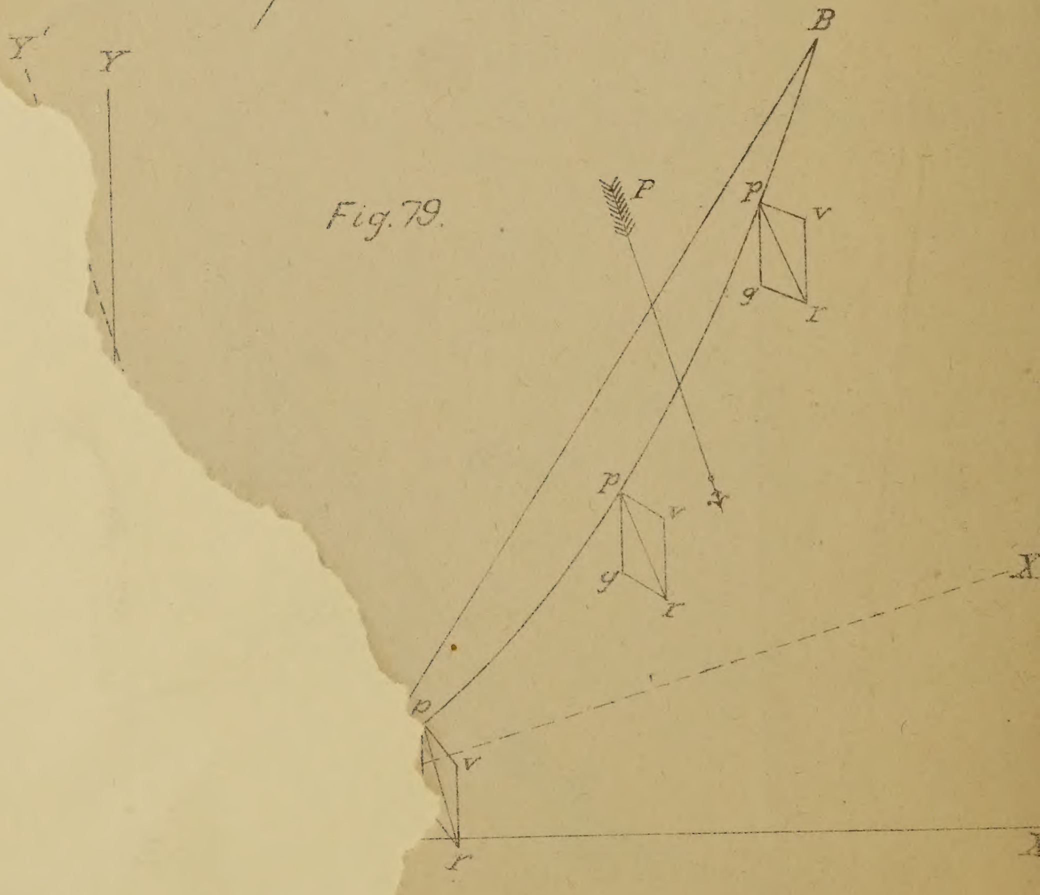

Fig. 79.